DROUGHT

its causes and effects

By the same author

Hurricanes: Their Nature and History
Weather Around the World

DROUGHT

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By Ivan Ray Tannehill

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TO GERTRUDE TANNEHILL

PREFACE

DROUGHT belongs in that class of phenomena which are popularly known as "spells of weather." A drought is a spell of dry weather. Other phenomena in the same general class are: "Indian Summer," the "January Thaw," and those spells of cold, rainy and other unusual conditions, some of which are supposed to follow certain indications of anniversary dates such as "Groundhog Day" and "St. Swithin's Day." These spells of weather last for an indefinite time, usually between a few days and a few weeks. They are in a different class from the phenomena charted on the daily weather map or the regular seasonal changes of the weather. Most of these spells of weather are associated with elements of superstition or popular misconception.

Drought is unique among spells of weather; it creeps upon us gradually, almost mysteriously, but its consequences are a terrible reality. Drought is one of the best examples of our helplessness before the broad-scale phenomena of nature. In spite of all the power man has developed, he has not been able to produce in all the world's history enough rain from the free atmosphere by artificial means to water a modest garden at a place and time of his own choosing. We look into a droughty sky knowing full well that the atmosphere contains ample water vapor for our needs, but we have no way of bringing it to earth. We see millions of acres of vegetation slowly burn up, but there is no fire that can be quenched; and even if there were, we would have no water with which to fight it. The rain deficiencies in a major drought amount to billions of tons of water.

We look through the literature in vain for an adequate explanation of drought. The Fourteenth Edition of the Encyclopaedia Britannica passes directly from "Drouet, Jean Baptiste" to "Drowning and Life Saving," and the index has only one entry under "drought" and that is "drought soils." The 1,248-page volume, *Climate and Man*, of the United States Department of Agriculture, prepared at the close of the greatest drought decade in our history and published in 1941, offers no explanation of drought. It has

only this to say: "As yet, however, no definite proof has been advanced to contradict the opinion that all such relatively short-term climatic changes are nothing more than matters of chance."

In the preface to "Reports on Critical Studies of Methods of Long-range Weather Forecasting" published in 1939 as part of the research project financed by funds appropriated by the Bankhead-Jones Act of 1935 to the Department of Agriculture "to conduct research into laws and principles underlying basic problems of agriculture in its broadest aspects," these were the conclusions, "It was demonstrated in the great droughts of 1934 and 1936 in the United States, that calamity can be averted through economic and social organization. But these droughts also emphasized anew that scientific research thus far has failed to discover those natural laws that may underlie the recurrence of drought, and to formulate those principles by which the time and extent of drought and other great changes in the weather might be anticipated."

In the face of these facts, it is obvious that we need a new point of view. This book is offered modestly as a first approximation of what that point of view should be. It steps out boldly into the unknown, where we have meager facts to support the conclusions, but in so doing it underscores the importance of the problem and the need for more of the basic facts from long-continued and representative observations of the weather on a world-wide scale.

The treatment of drought in this book is an example of the methods of "Synoptic Climatology" which I propose as a branch of the science intermediate between synoptic meteorology and climatology. It touches more intimately the basic controls of weather and climate than do either of the older branches of weather science.

The weather records used as a basis for the text are those assembled and published by the United States Weather Bureau and the data contained in *World Weather Records* compiled by H. H. Clayton and published by the Smithsonian Institution. Still more credit must be given to the thousands of men and women, many without compensation, who have gone faithfully to their posts day after day and year after year to maintain the weather

records of the world. These records will someday give us the complete answers to these questions which are so important in planning our national economy and conserving our natural resources.

As a further acknowledgment of sources of information, I pay my respects to J. B. Kincer, retired chief of the Weather Bureau's Division of Climate and Crop Weather. Kincer spent many years processing data in a form that is convenient for a study of the drought problem. Without the data compiled by Kincer, it would have been impossible to write this book.

The study of rainfall variations has been one of my hobbies for nearly thirty years. The ideas expressed here are my own and are not offered as the official views of any agency of the government. Nevertheless, it is a pleasure to record the fact that I have had full encouragement from the Chief of the Weather Bureau, Dr. F. W. Reichelderfer.

During the years when I was carrying on these rainfall studies, I had help from many persons. Among these should be mentioned Earl Thom, who helped during the late thirties with official and unofficial studies of world weather in relation to rainfall in the Southern Plains. In the final stages of preparing the manuscript I had assistance in different ways from a number of my fellow workers; the following is a partial list: Gordon Cartwright, Dorothy Kelbaugh, Francis Kohl, Marie O'Bot, Elza Lorimor, Maxine Foutes, Orpha Hulse, Clarence Jordan, and Charles Reeves. Herbert S. Bailey, Jr., of Princeton University Press has made a great many helpful suggestions.

Drought has been one of the world's greatest mysteries, and it continues to have many puzzling features. In this case, as in many others in meteorology, the results of research have been and to some extent will continue to be confusing, because they are connected with that great paradox in meteorology, "A hot sun makes a cool earth." The right answers seem to be the wrong answers.

IVAN RAY TANNEHILL

July 1946

CONTENTS

INTRODUCTION

CHOOSING A POINT OF VIEW

METEOROLOGISTS, in the past, have adopted one of two widely different points of view regarding weather and climate. The first, and the more generally accepted, may be called the *classical* point of view. The second, for lack of a better name, may be called the *objective* point of view. The majority of workers in the fields of weather and climate, sooner or later, consciously or unconsciously, adopt one or the other of these attitudes. The terms *classical* and *objective* are used here only for convenience of reference.

We all agree that the observed changes of temperature from day to night, from summer to winter, and other obvious changes are so clearly associated with our observations of the position of the sun that there is no question that the sun is the original cause of all weather changes. As we proceed from that fundamental beginning, ideas differ and diverge more widely.

The classical view is as follows: Climate is simply average weather. The rising and setting of the sun and the march of the seasons bring inequalities in heating and cooling of the earth's surface and the atmosphere. The temperature contrasts between the two hemispheres and between the continents and oceans are the dominant terrestrial factors. Mountains, valleys, plains, ice fields, cold and warm ocean currents, deserts, forests, cultivated fields, snow-covered ground, swamps, lakes, tropical seas, and all the other geographical features of the earth, large and small, have their influences.

According to this point of view the radiation received from the sun is essentially constant, and the changes in the weather are due solely to the great diurnal and seasonal variations that are produced in endless variety by the kaleidoscopic features of the earth and its atmosphere. For example, cloudiness in any area is not dissipated at once but moves, bringing new variety to the weather in adjacent areas. The earth's land surfaces may be snow-

FIG. 1. "The first rainless day in a spell of fine weather contributes as much to the drought as the last day, but no one knows precisely how serious it will be until the last dry day has gone and the rains have come again." Loading wheat in Indiana with fair-weather cumulus in the background. (U.S. Department of Agriculture, photo by Harmon)

covered and white, changing to brown and green with resultant changes in the weather. Storms of different kinds, arising from inequalities in heating and conflict of air masses, move on a variety of paths, each being its own master, but influenced to some extent by its predecessors. (Fig. 2.) When skies are clear and the atmosphere is calm, it is but a prelude to another storm, as new inequalities in heating produce innumerable small variations, some of which eventually dissipate or combine and survive, perhaps receiving new impulses from further diurnal or seasonal changes.

Within certain limits, the atmosphere over each part of every continent and ocean responds in a characteristic manner. The sum or average of these responses, in addition to the frequencies of certain elements and their extremes, is climate. When we have detailed records of all the weather changes at any place for a period of years, we can analyze them and describe the climate of that place, giving its normal condition, its typical seasonal patterns, a statement regarding the extremes, and other data which are purely descriptive of weather as it comes and goes in the long run. There are certain features which are fixed, more or less, and the remainder are fortuitous, but they seldom deviate far from the limits determined by the nature of the atmosphere and the earth's surface.

To deal with the weather from the classical point of view, we chart the weather of the moment in as much detail and over as broad an area as possible. The visible movements and changes are projected as far into the future as seems possible from physical considerations. The events of the future are foreseen only within a span of two or three days, as these weather changes and movements tend to lose their identities. We strain to see them farther in the future but the haze of fortuity leaves nothing in the distance except an indistinct convergence toward the normal pattern. On a chart of the earth, the major changes seem to endure a little longer, perhaps five days or a week. Then the grand pattern of classical climate emerges, leaving us nothing but an indefinite after-effect which we call persistence.

By classical methods, the problem is never solved. Each day

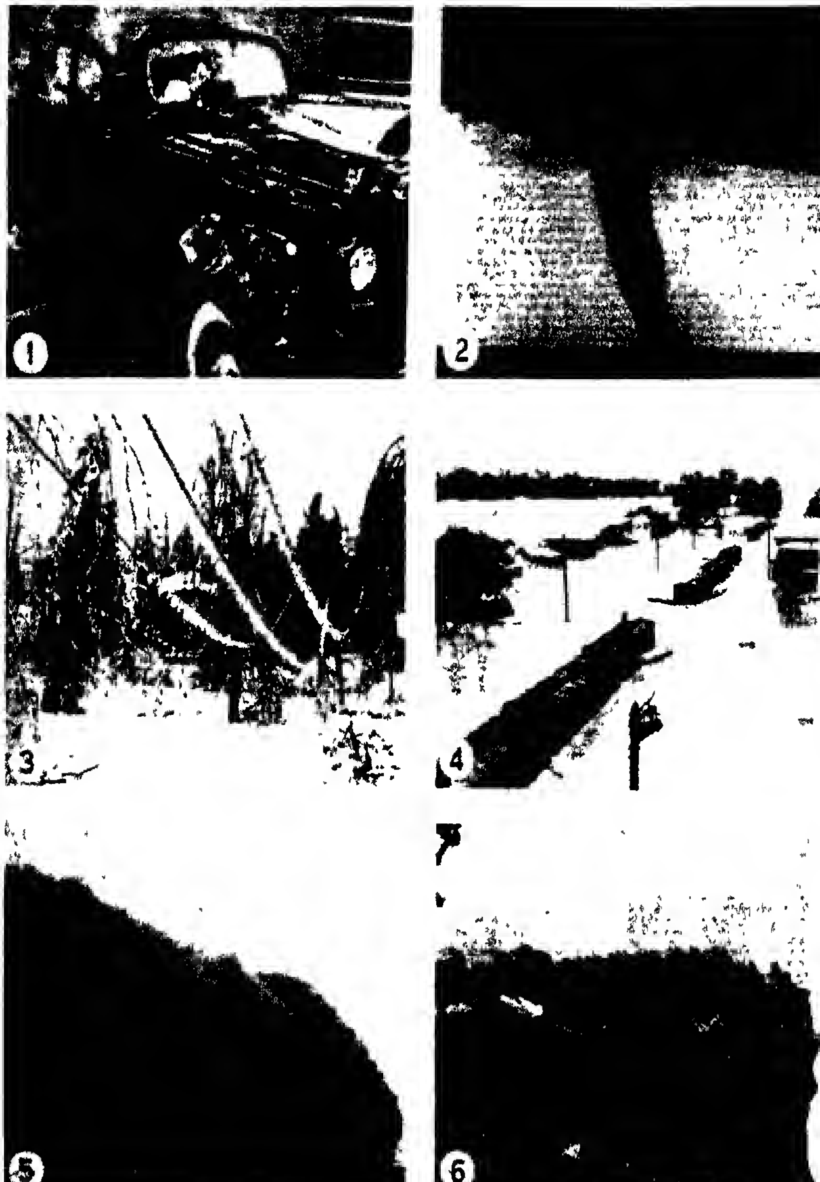


FIG. 2 From the classical point of view each storm is its own master, bringing (1) hail, (2) tornado, (3) ice storm, (4) flood, (5) dust storm, (6) hurricane, etc., according to forces originating within the earth's atmosphere. (U.S. Weather Bureau photos)

and hour bring new situations. Regardless of theories we must deal with the weather as it comes. Storms, floods, blizzards, hurricanes, and other phenomena engage our attention. Visibility, height of clouds, and other elements of the weather of the passing hour are vital for air transportation. Everybody is affected by the weather in one way or another. As it passes, data accumulate in the records as further evidence to establish the climate. From the classical point of view, there is nothing between weather and climate except the time required to calculate and record the sums, means, frequencies, and extremes.[1]

The other point of view is called objective. It is as follows: Climate is as changeable as weather. The basic controls of climate also control the weather. Here we take the view that if the radiation of the sun were constant, the diurnal and seasonal changes would be reduced almost to sheer monotony. May of one year would be almost if not quite like May of every other year. October of next year would be little different from October ten years ago. The objective view therefore demands *variations in solar radiation.* Every important deviation from diurnal and seasonal monotony must come originally from the sun itself. (Fig. 3.)

In other respects, the objective view embraces nearly everything that goes with the classical view. The two hemispheres, the continents and oceans, and the innumerable secondary features including mountains, valleys, plains, ice fields, cold and warm ocean currents, deserts, forests, cultivated fields, snow-covered ground, swamps, lakes and tropical seas, reflect the diurnal and seasonal changes and *in addition* the variations in the sun itself. May of this year is different from May of last year because of variations in solar radiation. The objective view, like the classical view, allows terrestrial forces to affect the weather. The eruption of a volcano and the dust it throws into the atmosphere affect the weather and in some degree the climate until the last trace of dust is gone. The main difference between the two views is that

[1] Nothing in this book is intended to imply any criticism of existing methods of charting and forecasting day-to-day weather changes and issuing warnings of impending unfavorable or severe conditions. Great progress has been made in recent years in daily weather charting and forecasting.

the objective view holds that the climate itself changes through the years and it attributes climatic changes to variations of solar radiation.

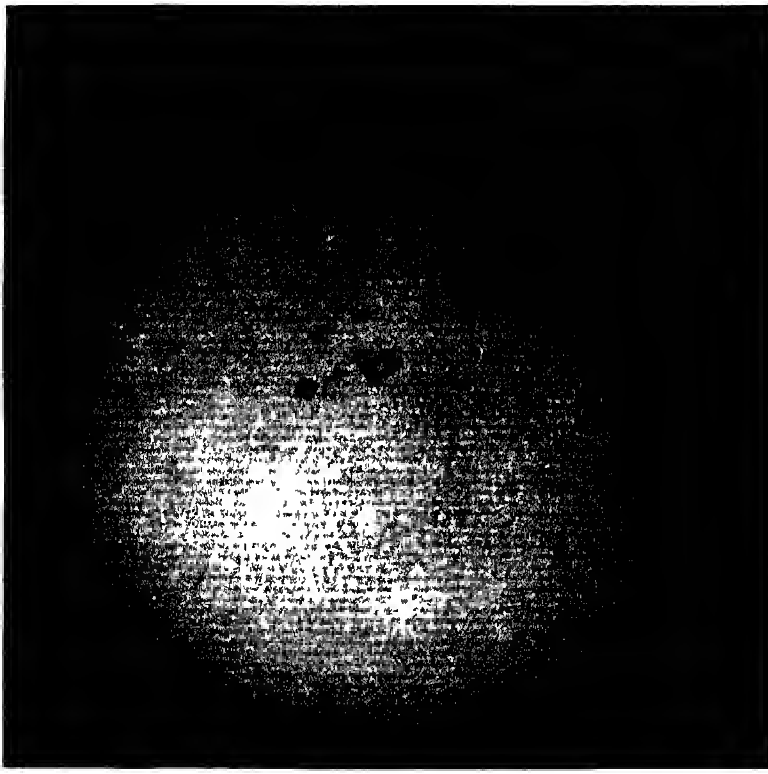


FIG. 3. From the objective point of view every important change in the weather comes from the sun, either directly or indirectly. Here we see the great group of sunspots which was associated with the magnetic disturbances and auroral displays of September 1941. (U.S. Naval Observatory photo)

Within the span of one generation the objective school has seen one of its brightest hopes fade. In the beginning, measurements of solar radiation indicated that the variations might be as much as five per cent, plus or minus. Refinements in methods of measurement and elimination of errors apparently have reduced

the magnitude of these measured variations to less than one per cent, plus or minus. This has been a severe blow to the objective school. Silently many of its members have gone over to the classical school.

There remain, of course, the sunspot cycle and other changes evidenced by visible activities in the sun. Even the classical school grants that there are small solar variations, probably within the margin of one per cent, but it declares that the effects of these variations are slight, that they are chiefly confined to the tropics, and that the effects in higher latitudes are small and difficult to identify in the turmoil of independent diurnal and seasonal variations which dominate the weather.

Choosing a point of view becomes important when we deal with the phenomenon of drought. If we take the classical view, we start with the assumption that a rainless day is a more or less independent incident in the run of weather. Two consecutive rainless days constitute a coincidence. Three rainless days make a chance combination. If this keeps on we have a drought. The frequency of certain combinations of rainless days is a feature of the climate of a place. There is a certain expectation of drought based on past records of rainy and rainless days. We do not assign the cause of the drought but we can explain each rainless day, and the sum total of these individual explanations must serve as the explanation of the drought.

If we adopt the objective view, we look for the basic control. We assume that a change in solar radiation has decreed that the rainfall shall be deficient. We look for the fingerprints of the dictator. For the time being, at least, the climate has changed. The sun, which determines the climate, has changed; and a train of events, which may include drought, will inevitably follow. We look for the train of events and seek to identify each step in the process beginning with solar variation so that we can see the drought coming and understand it as it develops.

The two divergent points of view have existed since the remote time when man first attempted to explain the weather and the climate. Aristotle and the other philosophers of his day were essentially classical in their views. For example, they gave names to

the winds and each, like Boreas, the North Wind, (Fig. 4) had a will of its own and seemed to come and go according to its independent disposition. The sun, of course, provided heat according to its regular daily and seasonal changes, but the "elements" were personified and were their own masters.

The objective view also has had its countless exponents in past centuries. It is exemplified by "moon farming," in which all the variations of the weather and the reasons for them are ignored. Planting is carried out in a certain phase of the moon, as though that alone guarantees the right kind of weather, either by the control exercised by the moon itself or by the association of its phases with some force which holds the destinies of the weather.

Fig. 4. "Boreas," the North Wind. According to the ancients, each wind seemed to have a will of its own, coming and going at its own discretion or in conflict with other winds—the classical point of view. (After Shaw)

Today we have the same division of thought. By weather mapping and air mass analysis we study the details of weather over a broad area at each moment of time. We predict changes and movements from place to place—the classical method. At the other extreme, we study the records of instruments thrust into the clear

atmosphere at the tops of mountains and try to translate variations of solar radiation directly into weather changes at the surface of the earth—the objective method. Consciously or unconsciously, we align ourselves with one or the other of these parties in the long struggle to explain the changes in weather and climate which are of such great concern to us and to future generations.

In this book we shall proceed with an open mind. First we shall look at the nature of the problem and see what drought, with its associated crop failures, famines, and dust storms, means to the peoples of the world; and we shall review briefly the history of droughts in the United States. Next we shall look at the facts in the case from the standpoint of weather. We shall review the rainfall records and related weather data and look for a clue. Third, we shall try to put together the pieces of this great puzzle and see if we have a satisfactory explanation and any hope of predicting drought in the future.

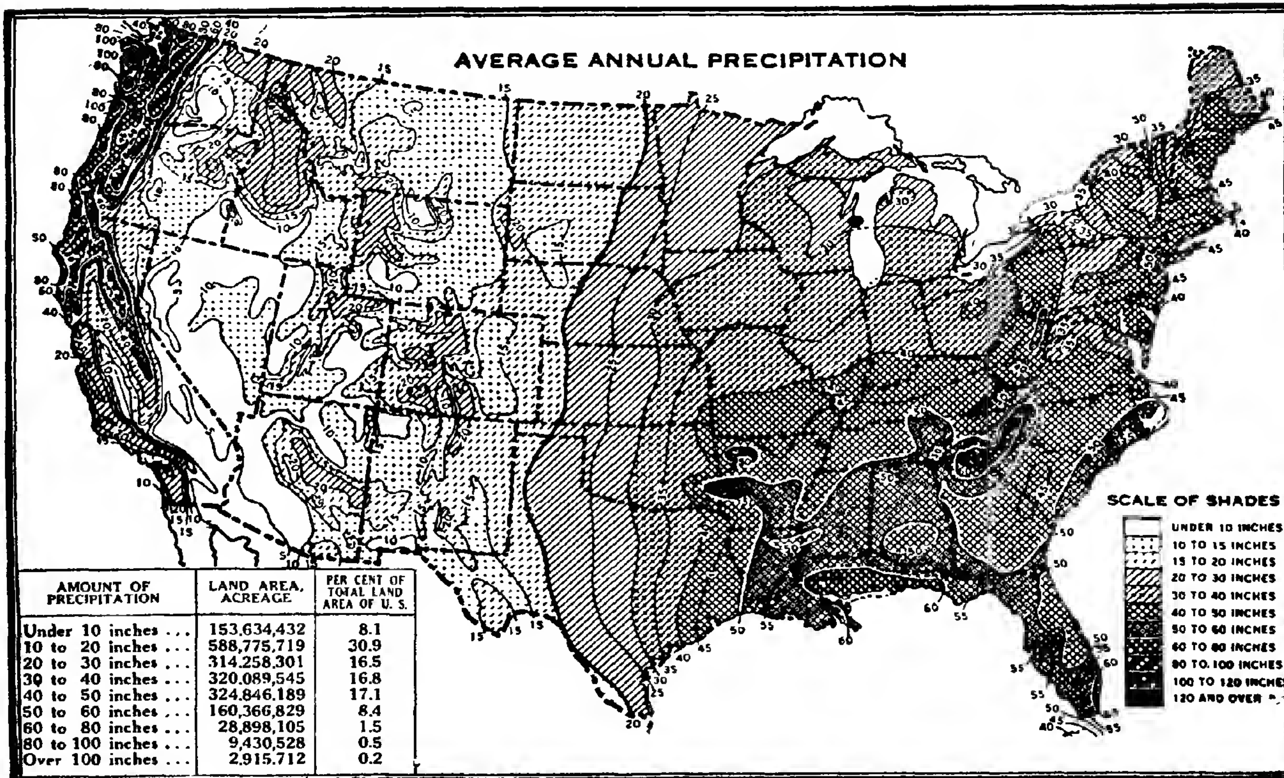
I. DROUGHTS AND THE MENACING DESERTS

THE United States is well-fed. That is because a considerable part of our country nearly always gets plenty of rain.[2] (Fig. 5.) Under normal conditions we produce more food than we need; nevertheless, drought has serious consequences. Any important widespread deficiency of rainfall in the United States, even for only a year or two, strikes at the very foundation of our national security as does nothing else except war or revolution. This fact has been impressed on us twice within the last sixty years when, in the depths of national depression, we were severely shocked by what we thought at the time was a broad-scale change to a drier climate.

Some early maps had the words "Great American Desert" written across the Western Range, including the plains in the western parts of Nebraska, Kansas and Texas. These words disappeared from our maps when we discovered that these vast areas are suitable for grazing and when the distribution of rainfall became more favorable after the middle of the last century. Following the Civil War, for a period of twenty years, there was increasing rainfall in the Great Plains. The generally accepted idea was that cultivation of the land had increased the rainfall. It was thought that the power of the soil to absorb moisture had improved and that the increase in soil moisture in turn caused an increase in the rainfall. Later this idea proved to be mistaken. Droughts became more severe, and now it is thought that cultivation had little to do with the amount of rainfall.

Our first experience with serious widespread drought started after the middle of the eighteen-eighties when the rainfall for the nation as a whole began to diminish. For three consecutive years in the nineties it was far below normal. It culminated in the great

[2] As used in this book, "rain" includes snow and other forms of precipitation, unless otherwise indicated in the text.



AMOUNT OF PRECIPITATION	LAND AREA, ACREAGE	PER CENT OF TOTAL LAND AREA OF U. S.
Under 10 inches ...	153,634,432	8.1
10 to 20 inches ...	588,775,719	30.9
20 to 30 inches ...	314,258,301	16.5
30 to 40 inches ...	320,089,545	16.8
40 to 50 inches ...	324,846,189	17.1
50 to 60 inches ...	160,366,829	8.4
60 to 80 inches ...	28,898,105	1.5
80 to 100 inches ...	9,430,528	0.5
Over 100 inches ...	2,915,712	0.2

Fig. 5. Average annual rainfall in the United States, including melted snow measurements. (U.S. Weather Bureau)

drought of 1894 and 1895. We had never known anything like it. It may have happened before we settled the vast interior of the continent, but this was the first great drought to put fear in our hearts. The rains returned and in the first decade of the present century we had plenty of rain, so we forgot temporarily about the drought problem.

Other droughts came, of shorter duration or purely local in character. We did not take them very seriously.

In 1929, autumn came to the California Coast without the usual rainfall. The rain deficiency was unprecedented. In 1930 there was a widespread drought east of the Rockies. There followed the "dustbowl" of the thirties, the "dusters" and "black blizzards," and repeated crop failures in the Great Plains. Soil which was found to have come from fertile western farms filled eastern skies. (Fig. 6.) With short breaks, the national rainfall was deficient for ten years, 1930 to 1939. Again fear struck at our hearts. Almost feverishly we began urging a change in our methods of farming. We went in for soil conservation on a large scale. The rains returned. Later a part of the "dustbowl" became a mudhole.

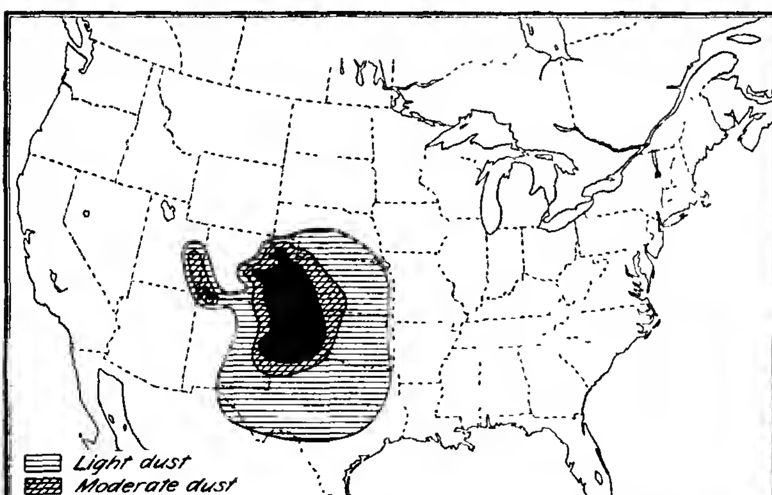


FIG. 6. The "dustbowl" in March 1936. (Choun)

During World War II we had an exceptionally good run of weather. Food was one of our best weapons. With farm labor at an extremely low ebb, we produced at top levels. We had plenty of rain.

Now what lies around the corner?

In looking for the answer to questions about droughts and deserts we must assume that their causes are much the same in all parts of the world. Every continent has a desert.[3] (Fig. 7.) Africa, which extends beyond the tropics on both sides of the equator, has a desert in each hemisphere. Surrounding every desert are areas where crops cannot be grown profitably except by irrigation. It takes large quantities of water to irrigate. We *must* have rain.

In times of drought on every continent people think of the deserts with alarm. Learned men write of our expanding deserts, our "deserts on the march." These alarming reports can be found in many parts of the world. For example, much of South Africa has a small rainfall and, like our high plains and western ranges, is suitable for grazing under proper controls but suffers from overstocking. Increasing dryness in South Africa culminated in a great drought in 1919. In 1920 the governor-general appointed a drought commission which gathered the opinions of experts in all matters relating to the drought and its terrible consequences, with particular emphasis on the possibility that a more or less permanent change to a drier climate was taking place. The commissioners said in their final report[4] in 1923 that "this drying out of extensive areas of the Union is still proceeding with great rapidity in many portions of the country. . . . *The logical outcome of it all is [that this country will become] 'the Great South African Desert' uninhabitable by man.*" (The italics are theirs.) They recommended radical changes in farming and grazing practices. They considered many questions about drought and its causes but got no satisfactory answers.

[3] There are two kinds of deserts: (1) the warm or hot desert where the rainfall is insufficient for vegetation to support a population, and (2) the cold desert where temperatures are too low for vegetation. The term as used in this book refers to the dry (warm or hot) desert.

[4] *Final Report of the Drought Investigation Commission.* Capetown, 1923.

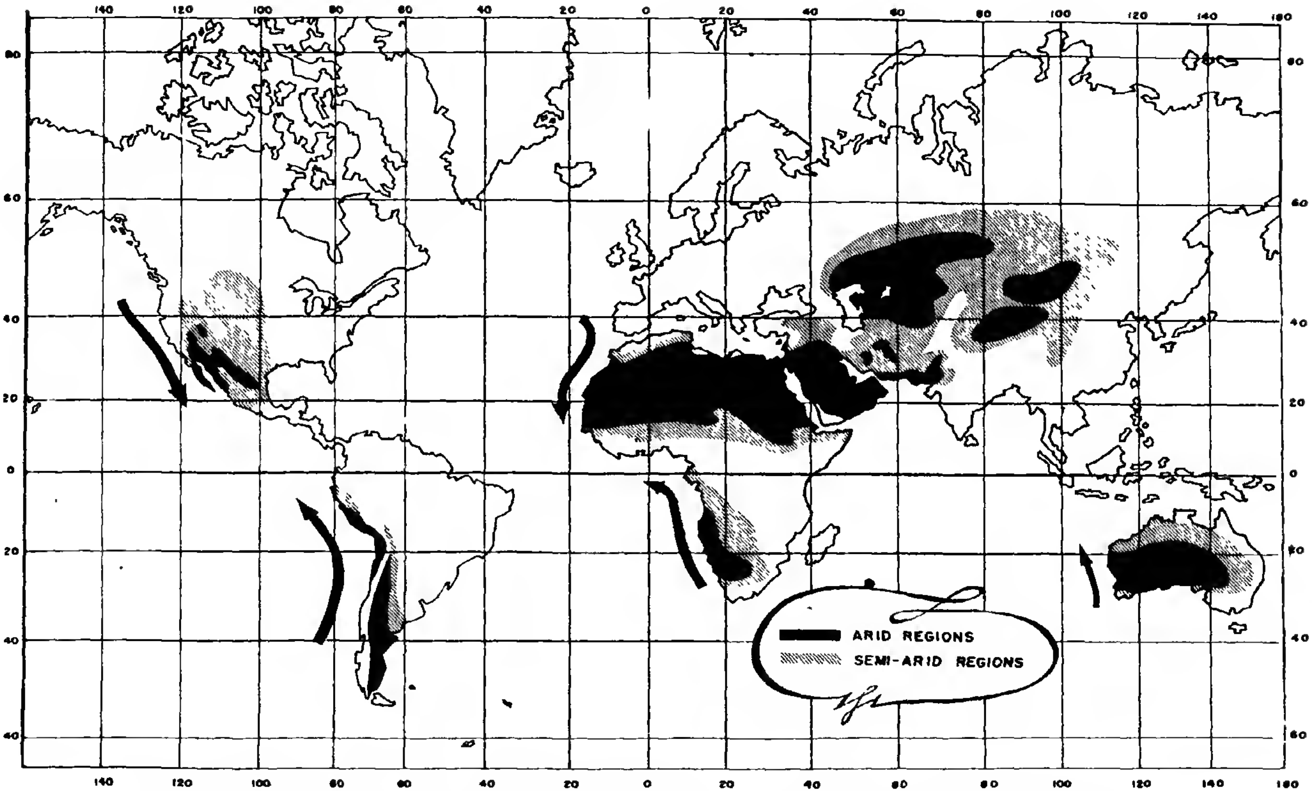


FIG. 7. Arid (desert) and semi-arid regions of the world. The black arrows show cold ocean currents.

In 1919 the Pacific Coast States also had a severe drought, but the remainder of the United States had a wet year. Fifteen years later we were in the depths of drought and depression. There followed the President's report on "The Future of the Great Plains" which paralleled the South African report in many respects. Indeed, the same thing already had been done in this country after the great drought of the nineties. In these miserable times we ask the same old questions: What is a drought? What causes droughts? Why are deserts located in the places where we find them now? Do they expand in time of drought; and if so, are they likely to take up a new or more extended position permanently? Are the forces that produce the deserts the same that cause widespread droughts? Can droughts be predicted? Are we experiencing a permanent trend toward a drier climate? These are questions of tremendous importance.

What is a drought? In the United States drought brings to mind withering crops, parched fields, dusty roads, and failing water supplies. In its extremes in some other countries it means hunger, famine, starvation, human emaciation and death, skeletons of animals, and mass migration of peoples. Sometimes it has led to war.

But we have no good definition of drought. We may say truthfully that we scarcely know a drought when we see one. We welcome the first clear day after a rainy spell. Rainless days continue for a time and we are pleased to have a long spell of such fine weather. It keeps on and we are a little worried. A few days more and we are really in trouble. The first rainless day in a spell of fine weather contributes as much to the drought as the last, but no one knows precisely how serious it will be until the last dry day is gone and the rains have come again. We ask if this was just a chance combination of dry days, or were we, even from the first, in the grip of some powerful force which might have been recognized?

What causes droughts? Weather experts have not given a satisfactory answer. Books on weather and climate mention droughts briefly or skip the subject altogether. Climate refers to average weather, or typical weather, but droughts in the United States are

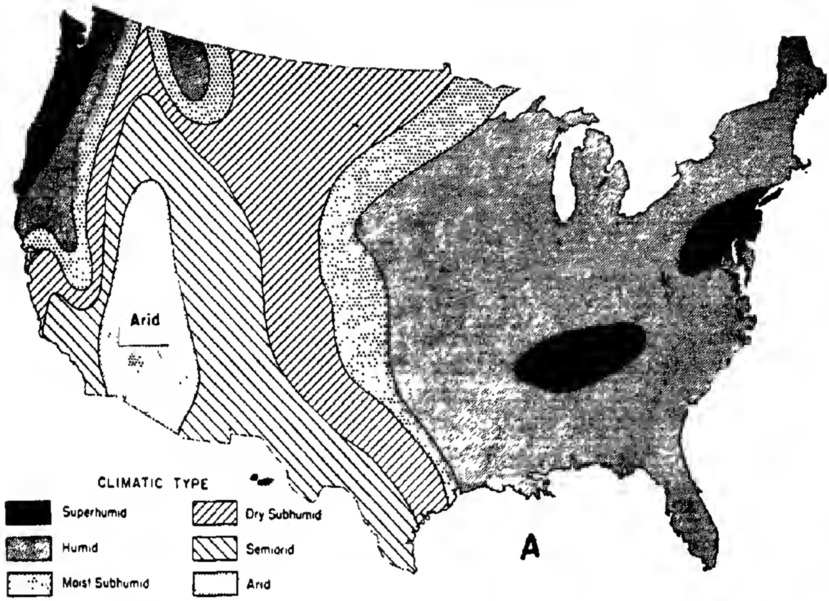
not average or typical conditions except in the Pacific States in summer and in certain other western areas where the climate is arid or semi-arid. (Fig. 8.)

For these reasons we may consider drought as a stepchild in the weather family—a sort of meteorological black sheep. At times it seems to violate the law of averages, the theory of probability, and all other rules. We might explain it as a change of climate but we have evidence that it has always been only a temporary condition. We are not sure about it until the crops have withered and died. There is nothing much that can be done until it is recognized as a bad drought, and then we come forward with government relief.

When a great drought proceeds day by day until it becomes a catastrophe, we speculate on the same old subjects: Maybe the ocean currents have shifted. Perhaps the climate is changing. During war time we talk about the effects of high explosives. Maybe the growth of radio broadcasting has affected the climate by putting too much electricity in the air! It may be due to the destruction of forests and the plowing of fields. Maybe we have built too many airports. Some scientists say that storm tracks have changed. Others think that it may be caused by too many sunspots or not enough. Finally, we gather in prayer.

Sometimes a rainmaker is engaged to add a few local puffs of gas to the earth's atmosphere or go through some other hocus-pocus or mumbo-jumbo. We seem to be ready to believe anything. Even in time of drought there are likely to be some spotty rains. Here and there we have a heavy shower. The rainmaker is ready to exploit the farmer's need for rain to save his crops. He installs his apparatus and waits. If he is lucky and rain or a heavy shower comes, he gets what he considers good pay from the community, perhaps a thousand dollars for each inch of rainfall. He asks for thirty days to produce the rain. If it fails to come he has lost nothing but his time, which is worthless anyway, so he folds his apparatus and silently departs to try again elsewhere.

Time goes on and a spell of fine weather has turned into disaster. We are caught off guard. In the beginning of a drought we never fight back. After all, how do we know that it is going to be



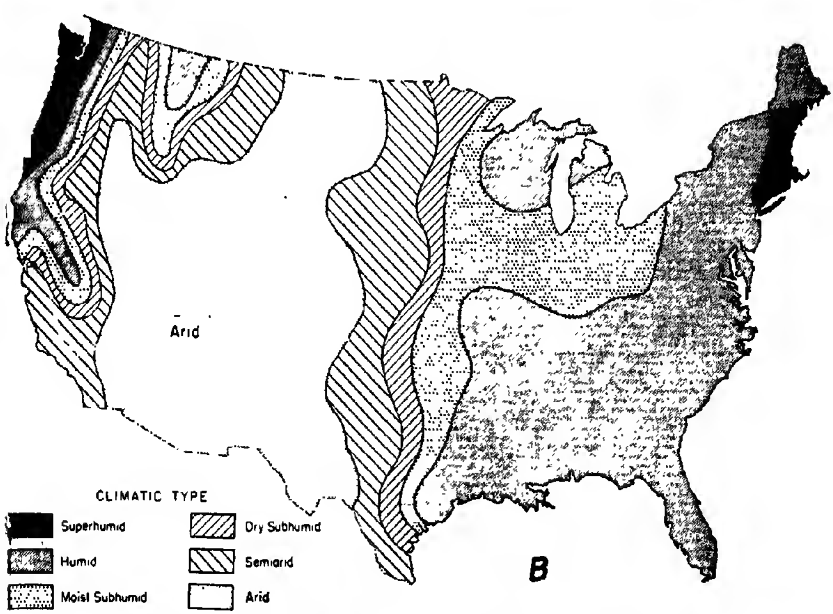


FIG. 8. Distribution of climatic types in the United States in (A) the wet year (1915) and (B) the drought year (1934). The expansion of arid climate in 1934 is noteworthy. See Chapter VI and Figure 31. (From Thornthwaite's Atlas of Climatic Types in the United States, 1900-1939)

a drought? It may be only another spell of fine weather to be followed shortly by more rain. It is the same with famines. Of one of the great famines of India, the official report said, "The Government appears to have been taken by surprise, and the severity of the calamity was not recognized until too late. Very little was done to relieve distress. The roads were strewn with dead bodies."

Each time there is a serious drought millions of words are written on crop failures, misuse of the land, overpopulation, rainfall records, etc. There are always many who claim that droughts come in cycles. There are many of these alleged cycles. They are of different lengths, from a few years to hundreds of years. Some think that droughts come and go in several different cycles, all working at the same time. This might explain their great irregularity, but it is not helpful. Even if we found drought cycles which seemed for a while to be borne out by the records, they would not be worth much unless they directed us to an understanding of the causes of drought.

In China there are fairly good records of droughts running back more than 1,300 years. They seem to come in an irregular pattern. There are some records of European droughts 500 years earlier than in China, but there is no apparent regularity in their occurrence. The droughts of China have been frequent over a long period of years, then much less frequent for a long time, then more frequent again. Records of water level in the Nile River run back to A.D. 641. Many other indications, including records of tree rings, varves, crop failures, market fluctuations, and other historical evidences indicate large variations in rainfall in past centuries. But there are no clearly defined cycles.

The countless droughts of past centuries have taken a tremendous toll of the world's peoples. The settlers may have thought that the New World would be free of such dangers, but as the population has continued to increase and we have continued to be prodigal of the natural resources of a new continent, we seem to be slowly but surely coming face to face with this terrible problem of the Old World.

What are the effects of drought? No one seems to have made a study of all of the economic disturbances caused by a major

drought. Some of the effects were traced by Ward[5] in an interesting study of a minor drought in July 1901. It was found that almost every branch of trade was affected by it. For example, the lack of pasturage in the Southwest led to record-breaking shipments of cattle and hogs to market at Kansas City. Here the receipts for July 1901 exceeded those of July 1900 by 263,000 head. The animals were shipped, not because the market invited them, nor because they were in the best condition, but simply because of their owners' inability to feed them. The markets were so overstocked that the buyers dictated prices—to the great advantage of the packers. Here was a case in which a minor drought led to an overabundance instead of a scarcity of important food products.

In 1901 the uncertainty about the corn crop led to hesitation on the part of investors in railway securities. The stock markets underwent rapid fluctuations with every slight change in the weather, actual or anticipated, until the drought was finally broken at the end of the month. Meanwhile, building was interfered with, and trade in paints, oils and other building requisites suffered. Meats were in less demand on account of the excessive heat, and wholesalers reduced prices in order to get rid of fresh meats. The consumption of milk increased greatly; hence there was a scarcity in many cities, which was due partly to the fact that farmers kept their milk for cream, instead of running the risk of its souring on the way to the cities. Thus it is obvious that even a minor drought like that of 1901 has serious economic effects.

The unparalleled drought of 1934 greatly reduced water levels in rivers and lakes, and navigation was impeded. Lightened cargoes resulted in losses. Lakes Michigan and Huron reached the lowest levels known. Communities were forced to extend water works farther into lakes due to recession of shore lines. Sewer outlets were left high and dry and became a menace to health. There were extensive relief works in twenty-four states. There was a 40% reduction in corn and wheat yields. The government

[5] Publications of authors mentioned in the text are listed in the bibliography.

purchased seven million cattle and five million sheep. It was estimated that this drought (1934) and the conditions preceding it did direct damage to agriculture amounting to five billion dollars.

Not the least serious of the effects of drought is the spread of forest fires. The litter on the forest floor becomes very dry, and low humidity, high temperature and fresh to strong winds produce "blow-up" conditions. Camp fires, smokers, lightning strikes in dry thunderstorms, and other causes of fires become exceedingly dangerous in droughty weather. A small fire spreads with great rapidity and is difficult to control under such conditions. The great Tillimook, Oregon, fire of August 1933 started from a tiny spark caused by the friction of one log being dragged across another in an active logging operation when conditions were just right for a blow-up.[6] The crew made immediate efforts to extinguish the flames, but the fire quickly "crowned," that is, spread to the top of nearby timber, and eventually burned over 261,640 acres and destroyed or damaged nearly eleven billions of board feet of standing timber.

The effects of forest fires in droughty weather are sometimes even more serious than the above remarks would indicate. When a large area is burned over, the local climate is changed. The soil is affected by erosion. The species of trees which grew in the area before may not thrive under the changed conditions. The land may be virtually unproductive for years and in fact may constitute a threat to towns and villages in the area. In California's chaparral-covered mountains, two canyons were visited by a general rain storm in December 1933. Twelve inches of rain fell. One of these canyons had been burned over. Its flood waters swept through a town, destroyed 200 homes, and took 34 lives. In the unburned canyon a few miles away, the storm rainfall was absorbed without flood or water damage. Thus the extremes of the rain cycle bring a cycle of tragedy—drought, fire, dust, and finally flood.

In nations that are older and more populous than ours, droughts

[6] Dague, C. I., "The Weather of the Great Tillimook, Oregon, Fire of August 1933." *Monthly Weather Review,* July 1934.

Fig 9. Above The shifting sands of the desert in Death Valley, California. (National Parks Service photo) Below Some of the deserts of southwestern United States are marked by the giant cactus (Bureau of Reclamation photo)

often grow into famine. More than ten million people have died in a single famine. It is a terrible problem in China, India, and other populous countries.

In America we have a drought problem, but it is not yet a question of famine. But it is characteristic of the American people that we like to cross our bridges only when we come to them. In times of heavy rainfall we talk of flood control and in times of drought we talk of soil conservation. We worry about emergencies and forget them as soon as they have passed on. We seem to be rather sure that our North American desert will stay where it is and that our rather extensive arid and semi-arid region in the West and Southwest will not spread out over us. (Fig. 9.) We accept them as permanent features of our continent, as we saw them in our school geographies. History and geology do not give us much comfort on this point.

There are brief droughts and long-continued droughts, local droughts and widespread droughts, and there are droughts preceded by good rains and others preceded by scanty rains.

Drought is too persistent a phenomenon to be the result of mere chance. Coincidences can occur, of course, but it is too much to believe that juxtapositions of rainless days in long sequences can happen as frequently as they do without some real cause behind them. We must look for the causes in the great elemental forces of the sun, atmosphere, continents, and oceans. We must examine the records of weather and climate and identify the withering hand that falls upon our farms and ranges every few years.

II. FAMINE

FAMINE, war, and disease are pictured in the Book of Revelation as the three deadly enemies of the human race. Drought of itself can bring on a famine. Drought can be a cause of war, which in turn contributes to famine. Drought and crop failure bring undernourishment and starvation, which in turn contribute to disease. The three go together—famine, war, and disease—and in seeking the facts about the results of drought, we find the three so intertwined that they cannot be clearly separated.

War drafts labor that should be cultivating the fields; it withholds labor required to harvest the crops; it destroys crops which have already been harvested; it consumes and diverts the existing stores of foods. One of the strategies of war is to blockade the sources of supply. If we add to this the misfortune of coincidence of drought and war, millions are threatened with starvation. But drought, when long continued, can produce these results without the aid of war.

War is spectacular but drought and famine are insidious. In the day-by-day and week-by-week starvation of a people there is no particular point at which the news breaks into the headlines. The tremendous task of bringing relief to millions of people suddenly overwhelms the authorities. Hoarding and thievery abound. There is suspicion of exaggeration and grafting. Famine and disease fall upon the people. Sometimes they desperately wage war to relieve their distress. Sometimes they are too weak to fight.

History shows that drought lies at the bottom of most famines.[7] Men who have studied the famines of India say that there is no doubt that these famines have been caused directly by failure of the annual rains. In China there are many famines that are due almost solely to natural causes, chiefly droughts, but some of them are due to heavy rains and flooding of the fields surrounding the shifting beds of China's rivers. There are many contributing fac-

[7] Walford, C., "On the Famines of the World, Past and Present." *Journal of the Historical Society*, 1878-1879.

tors, but failure of the rains is the principal cause in China and India. The same has been true of Europe.

Drought and famine are products of irregularities in the distribution of the world's rainfall. The earth is a rotating sphere, with its surface nearly three-fourths water. Moisture from evaporation of ocean waters brings rain to support vegetation on the continents. But these rains reach only a part of the continents. (Fig. 10.) Some parts receive practically no rain, year after year. The adjoining lands get insufficient rain, and there are vast marginal areas, some with great populations, which have barely enough rainfall even in good years.

The destinies of hundreds of millions of people are involved in the changes in the distribution of the rains.

At intervals, one or more of the world's deserts seems to be expanding. Crops fail and there is consternation among millions of people. In the afflicted areas there is seldom any food reserve. To the people of the lands of famine, the coming of winter without prospect of food means death. The peasant turns his hopeless gaze into the hot, cloudless atmosphere. But "all signs fail in dry weather." Many thousands are in the same terrible situation. Natural processes eventually will bring rain again, but surely it will be too late. Past experience does not offer any hope. The spirit of the watcher dies within him, but his body lingers in torture.

We can look upon drought as a valley of rain deficiency in the broad sweep of time and weather. We emerge from the valley and welcome a world of normal peace and prosperity; but even as we do, we may be slipping slowly down into another valley of rain deficiency. Rainfall in large areas of the world is exceedingly critical. When drought occurs, large populations become restless. Aimless migration follows. The world's supply of food cannot be divided in advance of the harvests. It is shared in accordance with the distribution of the world's rainfall. Its inequalities lead to conflict.

Nothing to eat! Do we understand what that statement means? Someone says that if it doesn't rain soon the crops will be a failure and everybody will die this winter. The problem is as old as

civilization. The Scriptures say, "And there was a famine in the land." In those days there were starving people, refugees, and mass migrations, just as there have been in recent centuries.

More time passes and still no rain. The future looks more and more hopeless. "The authorities will do nothing. Every official is a grafter." These remarks are heard on every corner; they can apply to any one of a number of countries.[8]

More than a fourth of the population of the world lives in lands of famine (Fig. 11) and nearly half of the remainder lives under the constant threat of deficient rainfall. When drought hangs on, "communities, for all the courage of their people, fall into decay, with poor schools, shabby houses, the sad cycle of tax sales, relief, aimless migrations."[9]

Time goes on and the drought continues. Crops have failed everywhere. Undernourishment is apparent. The chief topic of conversation is food. Hunger absorbs all thought. Here and there men are guarding potato patches. People are beginning to barter everything for food to store up for a few days ahead. There are beggars everywhere. They provide themselves with pails or bowls to gather the refuse from the tables of the well-to-do. Rinds of watermelon and pumpkins, potato peelings and bones make good soup. Locusts are helpful as a supplementary diet.

Everybody accuses the officials of stealing and robbing. They are not sure what kind of government they want, but they *do* want a change. "It won't make any difference. We'll all starve anyway."

Everybody has eaten the seed grain the government gave them for next year's crops. Things will be worse when all the grass, acorns, and locusts are consumed.

In one place there are thousands of children each receiving daily only a small chunk of coarse black bread and some watery soup. They look underfed and ill. The bread is made of acorns and grass. It gives them pains, but the pangs of hunger are worse.

[8] This description is a composite of facts concerning several great famines in Egypt, China, India, Russia, and other countries.

[9] This sentence refers to the United States! Quoted from *The Future of the Great Plains.* Document No. 144, 75th Congress, 1st Session.

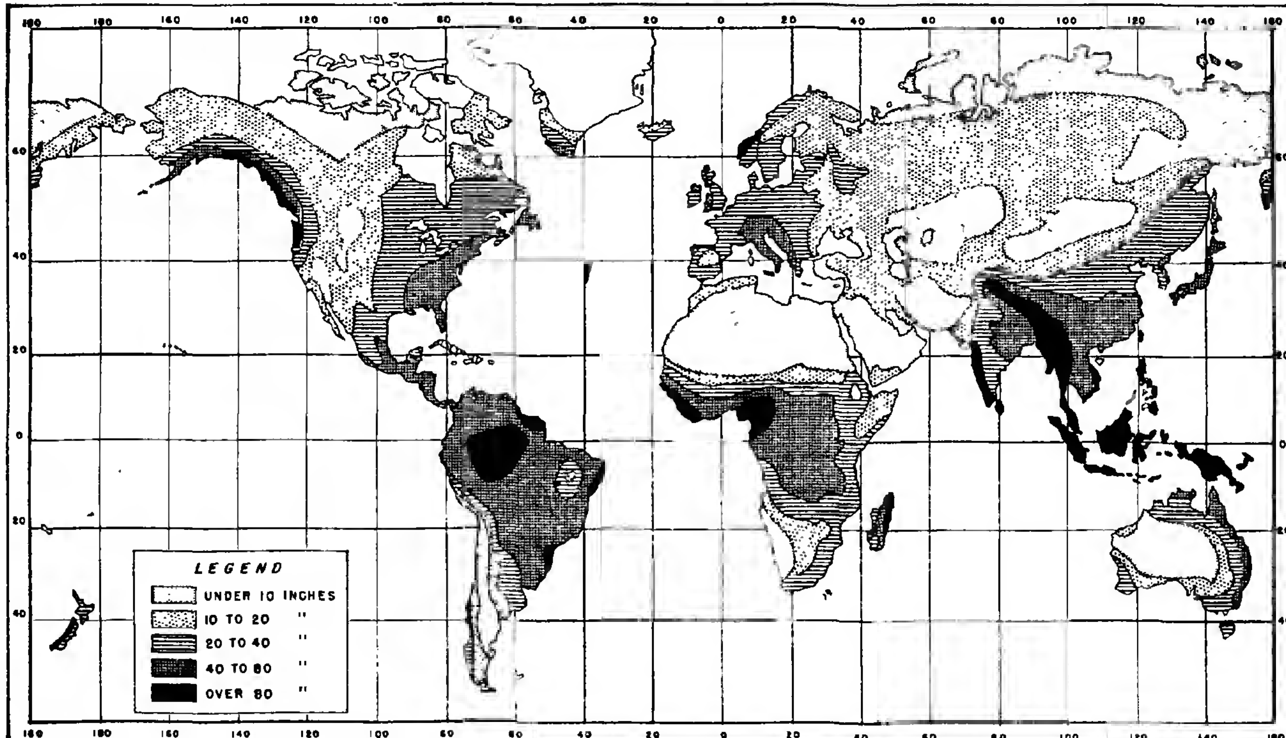


Fig. 10. Rainfall of the earth.

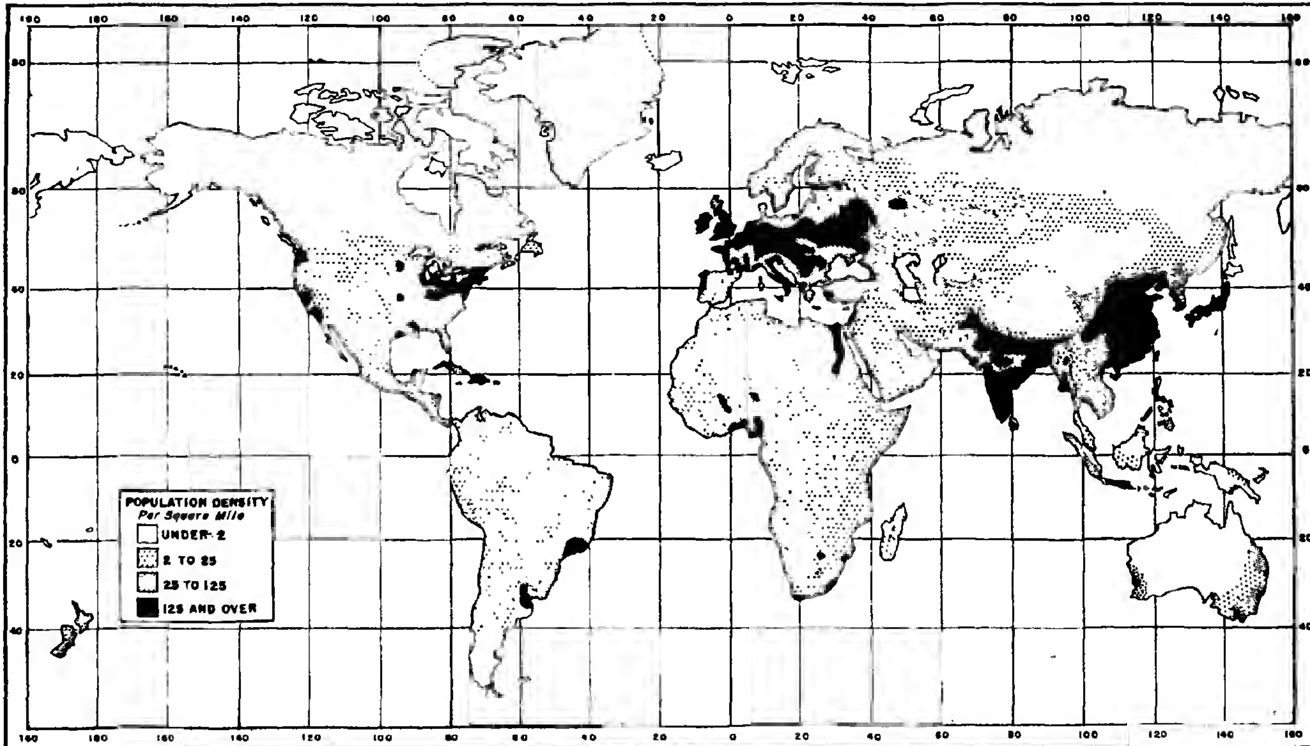


FIG. 11. Density of population, showing concentration in regions of Europe and Asia where distribution of rainfall is critical. Note the correspondence between Figures 10 and 11.

Dandelions and wild onions are gone and scurvy is breaking out.

The river banks are piled with household goods which the peasants hope to send away by boat in exchange for food. People waiting for boats live in the open in indescribable misery and filth. The chief occupations are sleeping and delousing. Someone who can afford the exorbitant prices sits down to a poor meal in a public place, and dozens of hungry eyes watch through the windows and bony hands reach out for the things on the table.

Bodies are swollen. Wailing parents and begging children flock through the streets. Shop windows are smashed. Refugees are flocking through. Ten to thirty are taken off the trains every day—some are dead from hunger and others from typhus, which is spreading everywhere.

Time passes on. Winter begins. Bodies stripped naked are lying helter-skelter; there are men, women and children, with limbs and features twisted and distorted. Others, like wounded animals, crawl quietly away to die. Still others in a state of stupor are indifferent, too weak to reach for a piecc of black bread if it is offered.

At last the government realizes the full gravity of the situation and begins shipping supplies into every available port. Cars, wagons and carts are all taken up for the trip through the mountains into the land of famine. Frightful disorder prevails along the route. Hundreds of officials and traders are intent on moving supplies through the mountain pass. The country is swarming with refugees, beggars, and thieves. The road is completely worn down and becomes impassable in places. Camels, mules, oxen, and donkeys are hurried along in the wildest confusion. So many of the animals die or are killed for their flesh by the desperate people in the hills that the remainder must be guarded by the militia.

Night traveling is out of the question. The road is marked by the carcasses and skeletons of men and beasts. Wolves, foxes, and dogs soon put an end to the suffering of any wretch who lies down to rest.

There are reports of cannibalism. In one of the cities gangs

lower hooks on the ends of ropes through latticed windows and drag miserable pedestrians from desolate streets to get their flesh.

At last a trickle of this enormous traffic begins to arrive in the land of famine. Distribution of food starts amidst disorder and violence. The government says with some satisfaction that this was one of the worst famines in the history of the country and yet not more than two million persons died!

The rains come again. The drought ends. All during the famine there were abundant rains and overproduction of foodstuffs in other countries where prices were driven down and people were made miserable and homeless by the hard times and floods. World economy has been shaken to its foundations. Unscrupulous men have come into power and everybody is afraid war will break out.

Droughts sometimes lead to war because the people of lands stricken by recurrent drought do not always submit tamely to starvation. When deficiencies of rainfall have developed slowly, so that the pressure on the population increased gradually, whole tribes have become savage and nomadic. Occasionally hordes of barbarians have descended on relatively defenseless peoples living contentedly in lands which have for the time being a more favorable climate.

History contains many examples of the rise and fall of civilizations. The evidence of deficient rainfall as the cause of many of these disasters is a subject of controversy. In most of these cases we have no very satisfactory indication of the amount of rainfall. The dwindling of lakes and the shrinking of glaciers are considered to be impressive bits of evidence, but there is little precise information about the rainfall. Irrigation, agricultural practices, erosion, destruction of forests, conquests, silting, and many other factors have to be considered.

It has been found, for example, that the Syrian Desert which now occupies a wide area between the coast range of the eastern Mediterranean and the Euphrates at one time was more thickly populated than any area of the same size in England except the immediate vicinities of large cities. It has been claimed that formerly there was more rainfall in that region than at present, but

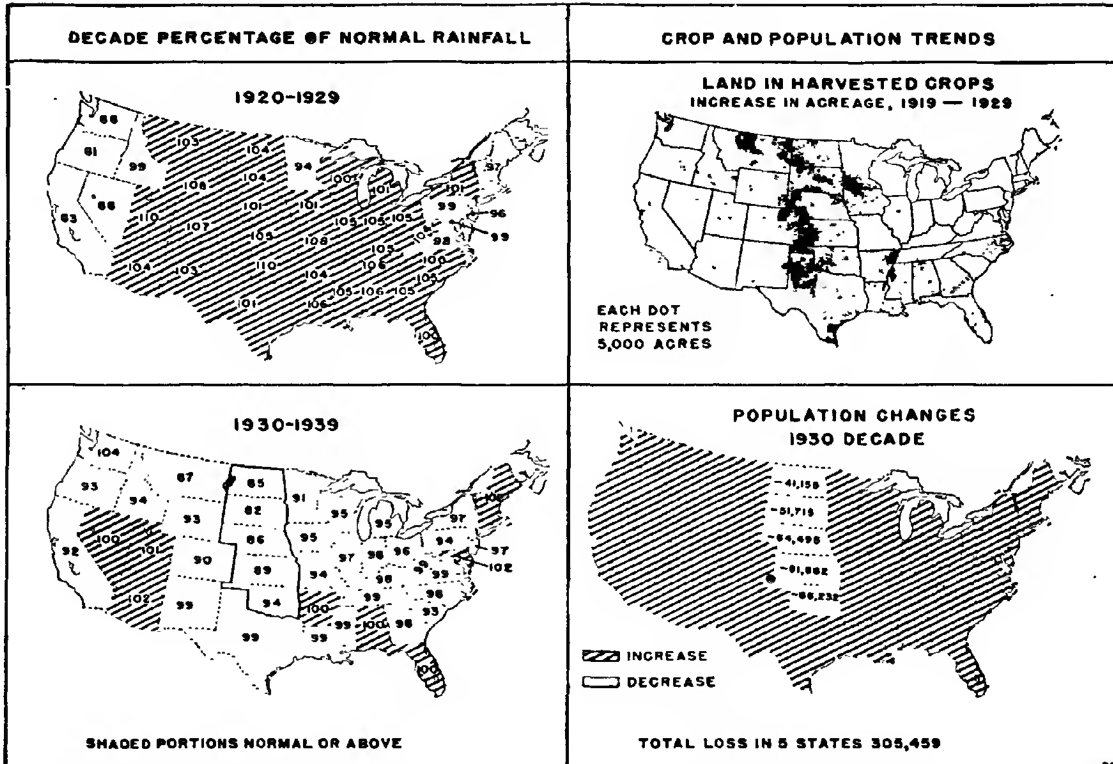


FIG. 12. Upper left, the rainfall of 1920-1929; upper right, increase in acreage of harvested crops, 1919 to 1929; lower left, the rainfall of 1930-1939; lower right, population changes in the 1930 decade. (U.S. Weather Bureau)

there is no certainty about it. The overthrow of the Roman Empire has also been attributed to dwindling rainfall.

The amount of rainfall required for agriculture is surprisingly critical. A relatively small but persistent change puts great pressure on the population. In the United States, for example, an average yearly rainfall of thirty inches or more for the country as a whole is decidedly favorable. When this national average falls below twenty-eight inches, there are severe droughts in some parts of the country, and a national rainfall below twenty-six inches has most serious consequences.

Records show that in the last sixty years the most favorable decade in the United States was from 1905 to 1914 with an annual average of about thirty inches for the country as a whole; the years from 1930 to 1939 were the worst with a national average of twenty-eight inches. The latter decade was featured by crop failures, dust storms, and a very considerable shift of the population. (Fig. 12.) If the rainfall over wide areas of the world has always been as critical as these figures indicate, we would require very accurate records of the rainfall to help in accounting for the rise and fall of civilizations in past centuries.[10] We lack records of such accuracy, but there is a strong presumption that variations in rainfall have been an important factor.

[10] Huntington, E., *Civilization and Climate*. New Haven, 1922.

III. DROUGHTS IN THE UNITED STATES

CONDITIONS have changed in this country. The Indian, the buffalo, and the passenger pigeon are symbols of conditions which will never return. Gradually the face of the land and, to some extent, the climate have changed. Written descriptions have remained, supplemented by the recollections of older inhabitants. But notes and memories are not of much use in establishing records of climatic changes. Instruments are needed to give accurate records, and the instruments must not be moved around too much. Many years of accurate records in the same location are essential for any worthwhile study of climatic changes.

Early travelers to the West were impressed by the change in the landscape when they emerged from the forests and headed across the plains. Their written impressions of the Great Plains have been preserved. But we must make allowance for their impressions of the contrast between the timbered lands and the prairies. Some of them described a great desert in parts of what is now the Western Range and parts of the Great Plains Region. There is much evidence to indicate that there actually were periods of very deficient rainfall in the second quarter of the 19th century. At the bottom of certain western lakes the tracks made by wagons of pioneers in the 1840's were later covered by water and remained covered for more than seventy years. (Fig. 13.) Tree rings tell almost the same story. It must have been dry in many parts of the country near and prior to the middle of the 19th century. The old records at and near St. Paul, Minnesota (Fig. 14), give additional evidence to this effect, but some droughts are local, and we cannot place much reliance on the records of a single locality.

Very little is known about droughts in the United States prior to the Civil War. This does not mean that in 1860 we knew little about the climate of the United States. On the contrary, Blodget[11] published in 1857 a climatology of the United States which con-

[11] Blodget, Lorin, *Climatology of the United States*. Philadelphia, 1857.

FIG. 13. Wagon tracks of the forty-niners where they crossed the floor of Goose Lake basin during the drought near the middle of the last century. These tracks were covered with water for more than seventy years and were revealed again for the first time in the droughts after 1920. Goose Lake lies partly in Washington and partly in Oregon. (Courtesy of the Geographical Review published by the American Geographical Society of New York)

tained a remarkably good appraisal of average climatic conditions in this country. The records of temperature and rainfall at that time were very short except in a few eastern localities. Weather stations west of the Appalachians prior to 1860 were few and widely scattered. Hence Blodget was obliged to deal in generalities, but he followed the techniques of European scientists who had much longer records to work with, and the results were excellent, considering the scantiness of the material. But we can draw no dependable conclusions regarding droughts from the scanty data of those times.

It is interesting to note that Blodget's rainfall maps (1857)

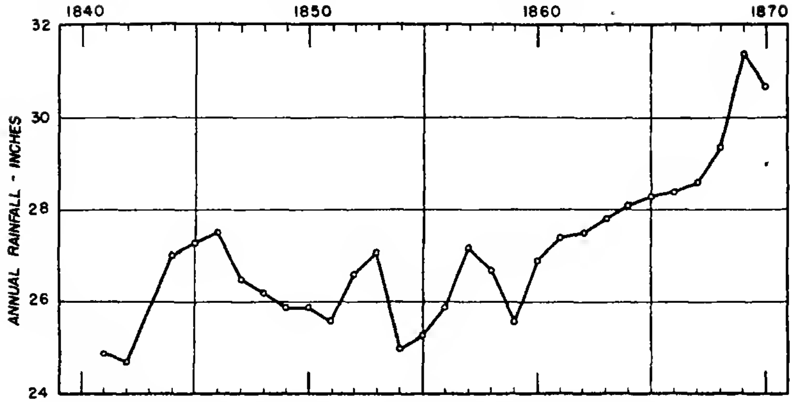


FIG. 14. Increasing rainfall at St. Paul, Minnesota, after the middle of the 19th century Averages for five years ending with year plotted

showed an area of the southern Great Plains marked "Desert Plains." It covered some of the same area that made the "dust bowl" of recent years.

In the third quarter of the nineteenth century the areas most frequently affected by drought, from the Mississippi Valley westward to the Rockies, were sparsely settled, and a deficiency of rainfall in that region was of no great concern to the nation. In the East and Southeast there were frequent deficiencies of rainfall, but the average rainfall there is ample, and a moderate deficiency seldom has affected total crop production seriously.

We find here and there in historical records references to droughts in the United States. There are two rather astonishing cases in New England.[12] They are astonishing because that region seldom suffers from drought even when there is a widespread drought in the remainder of the country. In fact, New England sometimes gets good rains in national drought years. This recalls the fact that when irrigation was first practiced extensively in the Southwest, there were complaints that it was causing increasing rains in New England. It was claimed that watering the land in the Southwest furnished more moisture to the air and increased

[12] Perley, Sidney, *Historic Storms of New England.* Salem, 1891.

the storms which came to New England from the West and Southwest. Time seems to have disposed of this idea and many others of the same kind.

One of the historic droughts in New England occurred in 1749. The spring months in that year were uncommonly dry. Grass appeared to be scorched by the sun, and pastures took fire and burned. The smaller rivers dried up. As the season advanced, conditions grew worse. The government ordered a day of fasting and prayer. Finally there were showers which gave some relief.

There was another bad drought in New England in 1762. It was similar to the one in 1749, but it was especially severe in eastern Massachusetts. A fast was held at Falmouth in Maine, but few attended because the men were busily engaged in putting out fires. The people were fearful that a famine would ensue. Rain came in great quantities in August; but, as in 1749, it was necessary to slaughter many of the cattle because they could not be fed through the winter.

The drought of 1860 was the most severe recorded in this country up to that time. Spring was very dry in Kansas, Missouri, Iowa, Minnesota, Wisconsin, and Indiana. There was a lesser drought in the same area in 1863 and 1864. From that time until the middle eighties rainfall was generally more plentiful and droughts less disturbing. The worst of this period occurred in August and September 1881. It affected the entire country east of the Mississippi. Many of the wells, cisterns, and springs that failed had never been dry before. Freight trains were seriously delayed by lack of water for steam. The water supply of New York City failed and it was necessary to draw from new sources. In this case, extreme heat began in July. There was great suffering in the cities. Hundreds died of the heat.

During these years the increasing population of the Middle West became conscious of the "hot winds of the plains." Hot winds have their greatest development in the region between the Rockies and the Mississippi. When these winds prevail, the air is very dry and the temperature rises above 100° F. They generally blow from the southwest from early forenoon to about 6:00 p.m. The hot dry winds of September 12, 1882, in eastern Kansas,

FIG. 15. Short grass of the Northern Great Plains before the days of cattle and sheep grazing, as seen in 1870 by the Hayden Expedition in Natrona County, Wyoming. (U S. Geological Survey photo)

burned the foliage of trees so that leaves crumbled to powder at the touch of a hand.

The first step in the production of hot winds is the failure of rains and the absence of cloudiness. Hot winds are therefore merely one manifestation of the conditions which cause droughts in the Great Plains. Although these winds are usually from the west or southwest, they sometimes come from the north and northwest after a spell of unusual heat. Their effects in the Great Plains are dependent to a considerable degree on the extent of grazing and crop-farming. It is safe to assume that the prairies did not suffer much from droughts prior to extensive settlement. (Figs. 15 and 16.)

The preceding remarks summarize briefly what little precise information we have regarding droughts in the United States prior to 1886. We have no accurate means of comparing these droughts of the past. Some numerical standard is needed, and we must have adequate rainfall records. From 1886 to the present time we have satisfactory rainfall records in all parts of the United States. These records will be discussed in detail. They are

presented in the Appendix. They will provide an indication of droughts in the years from 1886 to 1945.

Even with adequate rainfall records, we have difficulties in finding a measure of drought. Many writers have attempted to establish a numerical indication for comparative purposes. The element which immediately suggests itself is the amount of rainfall in a given period of time. Meteorologists have never agreed on such a definition. At one time in European Russia a drought was defined as a period of ten days with a total rainfall not exceeding a fifth of an inch. The U.S. Weather Bureau at one time defined a drought as a period of thirty days or more with deficient rainfall and not in excess of a fourth of an inch in any twenty-four hours. In England an "absolute" drought was defined as a period of fourteen consecutive days without a hundredth of an inch on any one day and a "partial" drought as a period of more than twenty-eight days with rainfall averaging not more than a hundredth of an inch a day.

FIG. 16. Overgrazed and wind-blown Nebraska sand hills; the original grass level was at tops of hummocks. (Soil Conservation Service photo)

Forty years ago the U.S. Weather Bureau tested the rainfall records of twenty places for drought, using as a requirement a period of twenty-one days or more with rainfall 30% or more below the normal. More than a thousand such periods were found; the average was more than thirty each year. By the same criterion the District of Columbia was found to have had sixty-two droughts in thirty-three years. During that time there had been four instances in the District of Columbia with rainfall less than a tenth of the normal for periods of thirty days or more. It might have been presumed that at least these four would have represented extreme conditions of drought, but this was not true. In most of the "drought" cases cited, there had been ample or heavy rainfall preceding the dry period, and there was enough soil moisture to support vegetation.

As records have accumulated through the years, other studies have been made in an effort to get a satisfactory definition of drought based on rainfall. One such study by Cole[13] in Arkansas, using a definition of fifteen days with no rain, gave about seventy droughts in thirty-three years. The study was based on daily rainfall records at stations in all parts of the State. Some had more and some less, but the average was more than two droughts a year. Most of them were really not droughts. Any more rigid definition, however, would have eliminated some real droughts.

Considered from the local point of view, as in the Arkansas example, drought records are quite confusing. From year to year they seem to occur more or less at random in different parts of the country and at different seasons. The rainfall records are kept on a monthly basis, and a drought beginning in the middle of one month and ending in the middle of another month may not be shown clearly in the monthly amounts. It is necessary to examine the daily records, but the results seem too confusing to justify the labor.

There is always the question of rainfall prior to the drought. It has happened frequently that a local drought has been preceded by rainfall considerably above the average. In other cases

[13] Cole, H. S., "Droughts in Arkansas." *Monthly Weather Review*, 1933.

the drought has been preceded by another period of deficient rainfall. Subnormal soil moisture, high temperatures, strong wind movement, and excessive evaporation make a moderate deficiency of rainfall more serious than a large deficiency under other circumstances.

Iowa, in the summer of 1934, is an excellent example of deficient soil moisture and high temperatures. It was claimed at the time that the cutting of trees, the drainage of lakes, ponds, and sloughs, and even the drainage of the land by tiles may have produced the drought. The same claim had been heard in the summer of 1894, which was twice as dry in Iowa as the summer of 1934. In the former case, the Weather Bureau calculated that if all the water in the streams, sloughs, ponds, lakes, etc., in the State of Iowa could have been evaporated and precipitated again evenly over the State the rainfall would have been but one-half inch, whereas the deficiency was about six and one-half inches. The truth is that the summer of 1934 was not seriously deficient in rainfall in Iowa, but the trouble developed because of three factors: (1) previous droughts had depleted soil moisture, (2) the 1934 summer temperatures were very high, and (3) the rainfall was very unevenly distributed.

Sometimes we scarcely recognize a local drought when we see it in the rainfall records. When the student of weather records begins to make a study of local droughts in the United States he becomes badly confused. He is confronted with the tremendous task of working all the records over again to fit his ideas of what a drought really is, or he is obliged to accept data which appear to be in a state of disorder so far as his particular problem is concerned. For example, the rainfall in the worst drought ever experienced in Ohio would be abundant moisture in Utah. (Fig. 17.) Vegetation in Ohio has adjusted itself to the normal rainfall there; that in Utah is dependent on a much smaller amount. It is not helpful to use the same measure of drought in both the West and the East.

From these facts we gather that it is useless to attempt to give a precise definition of drought. We can say that "a drought is a

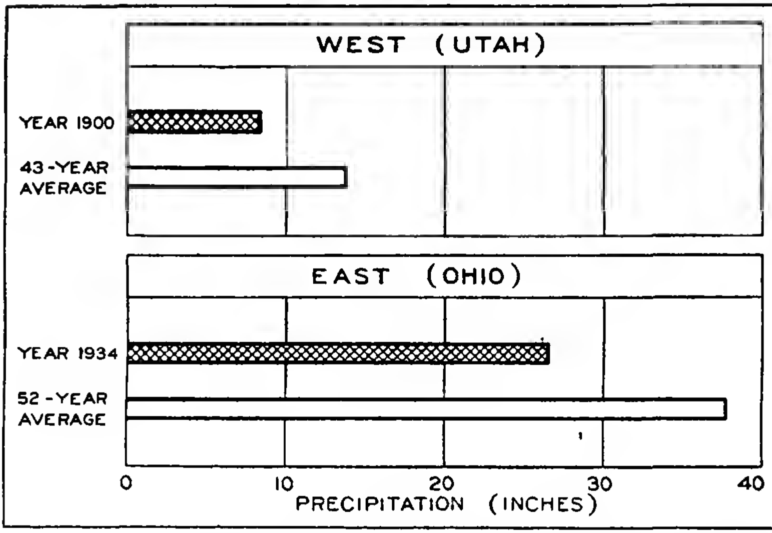


FIG. 17. The rainfall in the worst drought ever recorded in the East seems abundant when compared with the average rainfall on the Western Range, as shown by rainfall records for Utah and Ohio. (From "The Western Range")

period of deficient rainfall which is seriously injurious to vegetation" and let it go at that.

It is obvious that we must take a broader view of the problem, and for the time being ignore local and short-period variations in rainfall. To reduce the problem to as simple a form as possible, we can use the rainfall each year for the United States as a whole. This average, weighted in accordance with state areas, for 59 years from 1886 to 1944, inclusive, was 29.1 inches. During this time the wettest year for the country as a whole was 1905 with 32.8 inches, and the driest was 1910 with 24.6 inches.

Of course, we have no assurance whatever that the records of the last sixty years provide a satisfactory index to the intensity of droughts which might occur in this country in coming years. Neither have we any assurance that the floods in our rivers of past years will not be greatly exceeded in coming years. We feel sure that there have been profound changes in the climate of this

country in past centuries. We have no assurance that these changes of the past do not come from the same fundamental forces which cause our southwestern desert climate to expand and retreat from year to year.

The rainfall records kept at Washington, D.C., continuously since January 1, 1852, illustrate a local phase of the problem. During the seventy-eight years from 1852 to 1929 there were four years when the August rainfall was less than one inch, or about one year in twenty. There were only six years when September rainfall was less than one inch or one year in thirteen. Therefore, purely on the basis of chance, the likelihood of August and September each in the same year having less than an inch of rainfall was (1929) one in $20 \times 13 = 260$, or once in 260 years. There were twelve years with October rainfall less than one inch, or about one year in six. There were eight years with November rainfall less than one inch, or about one year in ten. This makes the chance of each of the four consecutive months, August, September, October, and November, in any one year having less than one inch of rainfall to be about one in $20 \times 13 \times 6 \times 10 = 15,600$, or once in 15,600 years.

In 1930 the rainfall at Washington, D.C., was as follows: August 0.62, September 0.76, October 0.28 and November 0.79. In other words, the drought of 1930 at Washington established a record that according to the rainfall of the previous 77 years would by pure chance have happened once in 15,600 years. For these four months the average rainfall at Washington, D.C., was about equal to the annual average at El Paso, Texas, and only slightly greater than the average at Phoenix, Arizona. There was evidently some persistent control which modified the climate temporarily.

As further evidence, we see that for the country as a whole, 1930 was the third driest year in the 59 years from 1886 to 1944. Furthermore, the same four months (August to November) in 1929 were the driest of record in parts of the Pacific Coast States. At San Francisco in 1929 the rain gages set a new low record for these four months. It is evident that this was a widespread and persistent deficiency of rainfall which culminated in a record-

FIG. 18. Scenes in the "dustbowl" of the thirties. (U.S. Weather Bureau photos)

breaking drought at Washington in late summer and autumn of 1930. This drought was a forerunner of the great drought of the middle thirties which produced the "dustbowl." (Fig. 18.)

After we had accumulated twenty or thirty years of good weather records in the United States, a number of investigators became engaged hopefully in the task of finding the basic cause of what they called "secular variations in rainfall," but the search proved to be fruitless. They thought that if the cause could not be clearly established, they might find a dependable cycle or combination of cycles; but they found none. This and other failures led to the conclusion that climatic variations require no influences outside the atmosphere itself. In other words, it was thought that the daily and seasonal changes plus inequalities such as are caused by land and ocean surfaces are sufficient to account for all climatic variations, thus reducing the problem to one of dealing with purely random occurrences. Chance is all that is left if we eliminate variations in the sun as the primary cause of these changes. Still, scientists have calculated that if the energy of the sun should be eliminated, the atmosphere would come to complete rest with respect to the earth's surface in about ten days. Certainly we must look closely for effects owing to variation of solar radiation.

IV. DUSTERS AND BLACK BLIZZARDS

HOT winds and dust storms are natural accompaniments of drought. The same basic controls which deprive us of rainfall also cause important changes in the circulation of the atmosphere. The heat and dryness of the air are caused not only by absence of cloudiness and failure of rain but also to a large extent by air from other than the normal sources. It is all a part of the same picture.

Dust and sand storms are not new in the United States. There has been a long series of them. In the years from 1930 to 1939 the nation became dust conscious because of the excessive wind erosion in the Great Plains and the large quantities of dust which were carried to nearly all parts of the East. Many people wondered where it would end, and whether or not there had been a change of climate. As is usual in such cases the answer came in a convincing fashion. There was increasing rainfall after the end of the decade; and for the nation as a whole, 1941 was the third wettest year in the entire period from 1886 to 1944.

Dust and sand storms are common in many parts of the world, chiefly in deserts and surrounding regions. Spectacular dust and sand storms are frequent in the vast desert regions of Africa and Asia. One is the Egyptian "haboob," which is a local storm carrying enormous amounts of dust. Masses of dust and sand several thousand feet high on a front ten to twenty miles wide sweep along at a speed of thirty miles an hour. In some cases there is a whirlwind pillar of sand which moves along with great speed. This is called a "zoboa."

Dust-laden winds are given special names in various parts of the world. The "sirocco" blows from the deserts of northern Africa into the Mediterranean area. It is hot, dry, and heavy with dust, but it becomes moist before reaching Malta, Italy, and the Adriatic. The "khamsin" is a similar wind in Egypt and the Red Sea. The "simoon" is a stifling, hot, dusty wind of the Arabian desert. It penetrates Palestine and Syria. The "shamal" is the same thing in

Mesopotamia. In Australia a hot, dry, dusty wind from the arid interior is called a "brick-fielder." In West Africa this kind of wind is known as the "harmattan" or "doctor." It blows great quantities of dust out over the ocean and sometimes impedes navigation in coastal waters.

There are special winds of this kind in the United States. One example is the "Palouser," which is a dusty wind in parts of Washington, Oregon, and Idaho. It is the despair of housewives in the cities and towns of the area. In addition to the dry dust there is sometimes light rain with the dust, leaving a muddy smear. These dust storms originate in the desert regions of eastern Washington and adjacent areas. They are called "Palousers" because the dust travels over the Palouse region of northern Idaho, eastern Washington, and northeastern Oregon. The aridity is due to the sheltering effect of the mountains. This is illustrated by the fact that Hanford in south-central Washington east of the coast range has a mean annual rainfall of only 6 inches while at Wynochee Oxbow, exposed to the winds from the ocean at the foothills of the southern Olympic Mountains in western Washington, the annual amount is 146 inches. In the arid regions east of the mountains there are frequent dust storms.

Even better known than the "Palouser" is the "Santa Ana" wind of California. It is felt as a gale, sometimes with much dust, in the coastal waters near Los Angeles. This is a wind of the cold season, caused by the accumulation of cold air over the desert areas of Utah and Nevada. As it descends to lower elevations its temperature rises and it becomes drier, as do all winds descending mountain slopes. Santa Ana winds sometimes burst across the coast line with great force.

Between 1930 and 1939 the Great Plains suffered a series of dry years with bad soil conditions. Crop farming in many areas which are more suitable for grazing may have been a principal cause. The resultant dust storms were the worst in the history of the country. They came to be known as "dusters" or in their worst form as "black blizzards." Strong west and southwest winds, and sometimes dry northwest and north winds, which produce dusters

and black blizzards, arise from the same causes as the well known "hot winds of the plains." Whether we have winds without dust or dusters and black blizzards is mainly determined by the condition of the soil.

As in the case of the droughts, the dust storms of the thirties were first felt seriously along the Pacific. The great drought of 1930 was preceded by an unprecedented drought in the Pacific coastal region in the autumn of 1929. The dust storms of the Great Plains were preceded by an extraordinary dust storm in Washington and Oregon (Fig. 19). There was a dry spell which was followed on April 21 to 24, 1931, by very strong northeasterly winds across both states. Dust was blown from the arid parts of the interior toward the southwest.

In this case a dust cloud of great magnitude blew over parts of Washington and Oregon and out over the Pacific Ocean. The force of the wind caused damage to buildings and blew many trees down. Forest and brush fires broke out, owing to wind and low humidity. The dust was so thick over the nearby Pacific that vessels at sea had the same difficulties as in a dense fog.

In the Great Plains region the first great dust storm of the drought years occurred in November 1933.[14] In this case dust was carried as far as New York. Soon millions of acres were affected. (Fig. 20.) The Great Plains, already dry, suffered terribly during the national drought year of 1934. In March of that year, dust was carried to the Atlantic Coast. Great dust storms in May 1934 aroused national anxiety.

Occupation of the Great Plains for agriculture began about 1885. The settlers made a livelihood by crop farming during three or four years of fairly good rainfall. Then there were three lean years and the great drought of 1894 brought complete crop failure and disaster. As many as 90 per cent of the settlers abandoned their farms in some areas.

In the big drought of the nineties there was a great deal of dust. The following are notes selected from the official records of the

[14] Miller, Eric R., "The Dustfall of November 12-13, 1933." *Monthly Weather Review*, 1934.

Fig. 19. Damage to orchards and buildings in the great dust storm in the Pacific Northwest in April 1931. (U.S. Weather Bureau photos)

Fig. 20. Dust accumulation around farm buildings and farm machinery in the Southwestern Plains in dust storms of 1936. (U.S. Weather Bureau photos)

Weather Bureau in the early nineties at Dodge City in southwestern Kansas:

> "April 8, 1890: At 10 a.m. the dust in the air was so dense that objects could not be distinguished 100 yards off. No one who could possibly remain indoors was on the street.
>
> "August 13, 1892: The wind raised such a cloud of dust that it was impossible to see over 150 feet ahead.
>
> "April 6, 1893: The dust was blinding and was deposited so thickly on office furniture that everything looked as though it were covered by a layer of dirt prepared for a hot-bed."

In the years following the drought of the nineties, there was more rainfall. Grama-buffalo sod replaced the bare fields, and the plains healed. Then came World War I and high prices. Crop farming was resumed on a large scale, and tractors and other labor-saving machines were introduced. Grain farming had spread widely by the end of the wet years from 1905 to 1915.

Drier years came. It grew steadily warmer with few reversals. These were the warmest years in the history of the Great Plains. Drought seemed to be chronic. Wells were dug deeper and deeper until there were cases where it took a gallon of gasoline for power to pump a gallon of water. The subsoil moisture was depleted to a great depth.

The desert seemed to be spreading into the Plains. (Fig. 21.) By 1935 top soil was blowing in tremendous quantities. At intervals there were winds of high velocity with spiraling masses of powdery dust. As time went on the dust, which was coarse in the beginning, was blown again and again and became exceedingly fine.

Dust drifted into feed stacks and covered the pastures. In some places, livestock died from starvation and suffocation. Wet blankets were placed over doors and windows. People covered their faces with wet cloths. Static electricity rendered automobile ignition systems useless. Motorists were stranded until the blows ceased temporarily, and then the ignition systems worked again. Many dragged chains to dissipate the electricity. Ranch homes were deserted. Drifts piled up and stopped trains and automo-

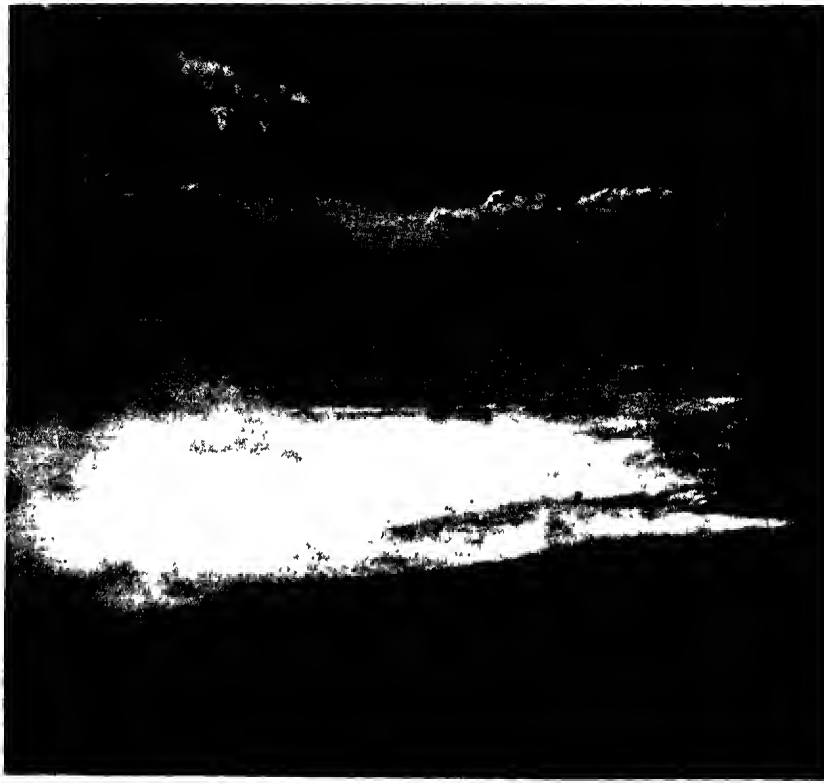


FIG. 21. View from airplane looking westward at the beginning of a dust storm over the prairie lands east of Denver. Just below the middle of the picture strong northerly winds are removing top soil from the prairie. In the background the dust is carried by southerly air currents aloft, capping the mountain range and rising to an elevation of 16,000 feet. Some of this dust was carried to the Atlantic seaboard. (U.S. Weather Bureau photo)

biles. Planes were grounded. Driving sand removed paint from automobiles and pitted windshields. During some of the storms, artificial light was needed at noon. Business was suspended. In some cases it was so dark from dust that pedestrians collided in the streets.

These conditions occurred at intervals for several years. At the end of March 1936 there was snow and in some places flurries of rain with the dust. There were mud showers, and muddy snow in the form of balls fell in north-central Colorado.

Drought brings other troubles. The grasshopper is one of the worst. Dry, warm weather is favorable for hatching grasshoppers, and a continued spell may bring a serious outbreak. In a single year grasshoppers in the United States have destroyed crops valued at more than one hundred million dollars.

Rainfall, especially with a continuation of cool cloudy weather, is unfavorable to young grasshoppers, chiefly by developing fungus and bacterial diseases which kill the insects in large numbers. Extreme drought may reduce plant growth sufficiently to starve the insects, but otherwise grasshoppers and drought go together. The insects destroy the vegetation and leave the soil susceptible to erosion, thus contributing to dust storms. For the five-year drought period from 1934 to 1938 the losses from destruction of crops by grasshoppers was estimated at approximately $315,753,000. (Fig. 22.)

Dust storms still continued in 1939, but the "dustbowl" had shrunk to about one-fifth of its original size, from 50 million acres at its worst to about 10 million acres. There was a national deficiency of rainfall in 1939 which temporarily revived the dust storms, but more rain came in succeeding years and the Plains had returned nearly to normal in time to meet the demands of the nation in World War II.

The damaging effects of drought are due not only to the lack of rain, but to the drying effects of winds, usually warm or hot winds which frequently prevail when rainfall is seriously deficient. Vegetation already deprived of needed moisture is subjected in addition to the desiccating action of dry winds under cloudless skies. In colder latitudes agriculture prospers with much less rainfall than is needed in warmer latitudes because evaporation goes on at a much slower pace. The principal point here is that the circulation of the atmosphere is different in drought years from that in years with normal or above-normal rainfall.

A long drought seems to kill all plant life, but vegetation has tremendous recuperative powers. When livestock nibble the grass to its very roots and the soil begins to blow, the gloomiest predictions are heard. The people who have worked the Plains through two or three generations and the families who have financed

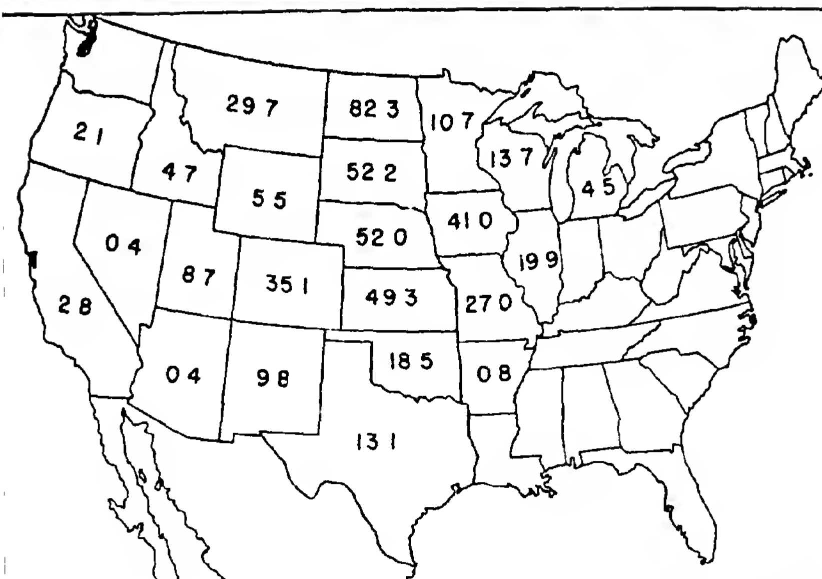


FIG 22 Above Grasshopper damage to corn Frequently all the stalks in large fields are eaten to the ground (*Bureau of Entomology and Plant Quarantine photo*) Below Grasshopper damage in millions of dollars from 1934 to 1938 (J R Parker)

farmers through years of distress have complete confidence in the ability of the land to come back. They know that basically it is a problem of weather. For them the only serious question is, when will the rain come? And when it does come, the land seems to spring to life again.

There is astonishing evidence on this point. On the west coast of South America there is a cold ocean current along shore, and there is normally a desert in the coastal area of Peru. At intervals of several years, the cold current weakens or is replaced by a warmer current from the direction of the equator. When this happens there are heavy rains which soak the Peruvian desert. Within a few weeks the whole country is covered by abundant pasture. Cotton can be grown in places where vegetation is impossible in other years. The desert becomes a garden. Weeds of many kinds grow rapidly. After the rains cease, the grass on the desert withers, but it forms a natural hay which affords goat pasturage for a year or two. Cases of this kind give strong proof of the recuperative powers of the land.

On the other hand, there is little doubt that continued overstocking of the ranges and the farming of lands unsuitable for cultivation result in some permanent injury. The density of vegetation may be seriously reduced. Grasses make remarkable growth when the rains come again, but the stands are thinner and it takes three to five years for reasonably good recovery. Soil erosion may leave permanent scars. Each severe drought removes a large acreage from profitable production for a temporary period, tending to increase stocking of the remaining lands. But these problems of land use do not directly concern us here. If we can answer the drought question, all the other questions will assume proper proportions.

V. WHAT MAKES IT RAIN?

ALL of the moisture for rain and snow on the land surfaces of the world comes originally from the oceans. The restless winds of the earth's thin envelope of atmosphere sweep over vast stretches of ocean surfaces. By evaporation, warm ocean waters yield great quantities of moisture to the atmosphere. Cooler waters yield less in proportion, especially when the water is cooler than the air above it. We are vitally concerned with the distribution of this moisture. Man's existence on the continents depends on the action of the atmosphere in carrying moisture from the oceans to the continents. The complicated mechanism is not altogether satisfactory from man's point of view.[15] Vast land areas receive very little rain or none at all.

The sun is the power behind the world's rainfall machine. As seen from the sun, the earth is a mere speck more than ninety million miles away. The earth intercepts only an infinitesimal part of the energy which the sun broadcasts into space, but this infinitesimal amount is enough to power our great rainfall machine. The sun heats the continents more in summer than in winter The oceans change temperature more slowly than the continents. There is nearly always a powerful temperature contrast between the hemispheres, between the oceans and continents, and between the tropics and poles. This keeps the atmosphere in motion and brings moisture to the interior of the continents.

The earth turns on its axis, and we have changes of temperature between day and night. The earth, with its axis at a slant, moves around the sun and so we have the seasons, as first one hemisphere and then the other is turned toward the sun. The earth's orbit is

[15] The causes of individual rains involve much detail in the study of storms, air masses, and fronts shown on daily weather maps. These are not of a time scale appropriate to this discussion of drought. For a treatment of daily conditions, there are standard works on synoptic meteorology; for example, Byers, H. R., *General Meteorology*; Petterssen, S., *Weather Analysis and Forecasting*; and Weightman, R. H., *Forecasting from Synoptic Weather Charts.*

not circular, and in the Northern Hemisphere we are nearer to the sun in winter than in summer. All these changes tend to produce a great variety in the sweep of moist winds from ocean to continent and back again. These seasonal changes increase the efficiency of the world's rainfall machine so that it scatters the moisture instead of dumping it all in a few places.

The rains and snows which fall on the continents are scattered again by other processes. Vegetation returns moisture to the air and it is scattered again. Rain and snow in the mountains supply water for the streams that flow to the plains and finally to the sea. The housewife's washing dries and gives moisture to the air. Lakes and rivers contribute by evaporation. We breathe moisture into the air. It is scattered again. Much of the moisture in the air is second-hand. It comes from the oceans originally, but is evaporated again from other sources.

Originally there are great inequalities in evaporation. The Southern Hemisphere is mostly water while the Northern Hemisphere has large continents. There are vastly greater amounts of original evaporation in the Southern Hemisphere than in the Northern. What happens as a result of this inequality in the two hemispheres is not altogether clear. The explanation in part is as follows: In our summer the heat equator extends into the Northern Hemisphere. Moisture is carried northward across the geographical equator. Some is used in the torrential rains of the hurricanes, typhoons, and other storms of our hemisphere. Vast quantities come northward across the equator in the Indian Ocean to pour on the high lands of India and Burma. Some of the moist winds blow over hot desert regions and finally come out again to deposit their moisture in some northern region. Vast air streams bring moisture across the equator, through the East Indies, and to the populous lands of China, where hundreds of millions of people await the summer monsoon rains.

In all parts of the earth where mountains block the movement of moist winds, there are great amounts of rain or snow. Glaciers and snows and lakes and streams in the mountainous areas of the world represent a vast rain reserve to provide for the future. Still,

Fig 23 Glaciers and snows and lakes and streams in the mountainous areas of the world represent a vast rain reserve to provide for the future Maligne Lake, Alberta (National Parks of Canada photo)

rain is not scattered far enough or regularly enough to prevent the occurrence of deserts and large scale droughts.

The energy from the sun which strikes any portion of the earth's surface varies from day to night and from season to season as the earth turns on its axis and revolves about the sun. But these changes are regular and predictable. If they were the only factors, we could analyze the waves of the atmosphere that move and are reflected around the earth and predict the weather for years to come. Local factors have some effect, of course, but they could be taken into account. There is, however, another important variation, imperceptible except to delicate instruments but with vast effects on climate and weather. This is the variation in the actual heat of the sun.[16] We shall see how the sun's variations correspond with the expansion and contraction of deserts and the occurrence of droughts.

The earth's rain machine has two jobs. It must draw the moist winds from the oceans to the continents, and it must take the moisture out of the air while it is passing over the continents. Vast quantities of moist air could pass over the continents and back to sea again without producing rainfall unless there were a mechanism for causing the moisture to condense and fall as rain, snow, hail, or some other form of precipitation. Droughts can and do develop while moist air is flowing across the land. In fact, most of the deserts of the earth are swept by winds which contain a great deal of moisture, but it is seldom precipitated there.

Within an equal volume, warm air can contain a larger amount of moisture than cool air. (Fig. 29.) Rain falls because the temperature of hot moist air is lowered and it is forced to give up some of its moisture in condensation and precipitation. Cooling the air for precipitation is an important part of the problem. Sometimes it is necessary for air to travel great distances along the earth's surface before it is cooled enough to produce condensation and rain. In summer, the warm moist winds from the Gulf

[16] The sun is a star and, for all its power, it is actually almost the smallest and faintest of all the stars visible to the naked eye. If its variations were great, the changes in weather would overwhelm us.

FIG. 24 Heavy rain clouds over Mount Shasta, California, August 1935, before excessive rain that destroyed Southern Pacific Railway track. (L. H. Daingerfield photo)

of Mexico might travel to Canada and find it as warm there as in Texas or Louisiana.

A comparatively warm layer of atmosphere covers the surface of the earth, but only a few miles up the atmosphere is very cold If some means is available to push the warm moist air of the lower altitudes up into the cold region, the moisture will condense and precipitation will occur. When warm, moist winds come to a mountain range and are cooled as they are forced up over it, heavy rain or snow is likely to fall on the slopes of the mountains facing the wind. (Fig. 24.) On the other side of the mountains there is little or no rain or snow. The heaviest rains in the world fall on mountain slopes facing winds which blow from the oceans. There are more than 400 inches (nearly four feet) of rainfall on favorable slopes in Burma in one year. As much falls on Mt. Wailaieale in the Hawaiian Islands. The heaviest rains in North America fall on the slopes of the coast range facing the winds from the Pacific blowing into Oregon, Washington, British Columbia and southern Alaska.

Fig 25 This is not a dust storm "A mountain of cold air can be as effective in causing rain as a mountain of rock" Above A cold front near Brownsville, Texas, at noon, February 18, 1942 Below Same, 5 minutes later (Pan American Airways photo)

A mountain of cold air can be as effective in causing rainfall as a mountain of rock. (Fig. 25.) But a mountain of cold air can move around so that all the rain that is taken out of the air does not have to fall in one place. When a mass of cold air comes down from Canada and warm moist air from the Gulf of Mexico or the Atlantic Ocean is forced up over the cold air, there is cooling, condensation, and precipitation. As the mountain of cold air moves farther to the south or east, the warm moist air is forced upward in new places and thus the rain is scattered.

When air is heated locally it may be forced upward by surrounding air which is more dense, and a local thunderstorm may develop. (Fig. 26.) In the hot season, local thundershowers sometimes bring enough rain to break a drought. At other times local showers are widely scattered and the drought may be spotty. In any case, there are few places in the United States where the rainfall from purely local showers affords dependable moisture for crop farming. Cool masses of air must be present occasionally, at least, to force the warm moist air upward in large enough quantities to produce the rain we need.

As long as air is becoming warmer and drier instead of colder, no rain falls. Sometimes in spring or summer plenty of warm moist air from the oceans blows inland, but the continent is warmer and the moist air gets warmer instead of colder, and no rain falls. If there is no mass of cold air in its path in the United States, warm moist winds may blow across the country and curve into eastern Canada before the air is forced upward over cold air to make rain. In such cases there are sunny days, sometimes getting warmer and warmer. Day after day the exasperated midwestern farmer sees fleecy clouds pass over, sometimes with heat lightning on the horizon in the early evening, and no rain falls. (Fig. 27.)

One of the causes of failure of the rains in the Great Plains is the rotation of the earth. In the Northern Hemisphere every wind that blows over the earth's surface is turned to the right. Warm moist air may start moving from the Gulf or Atlantic toward the heated plains. It may even be directed toward the foothills of the Rockies, but the rotation of the earth deflects the moist air stream

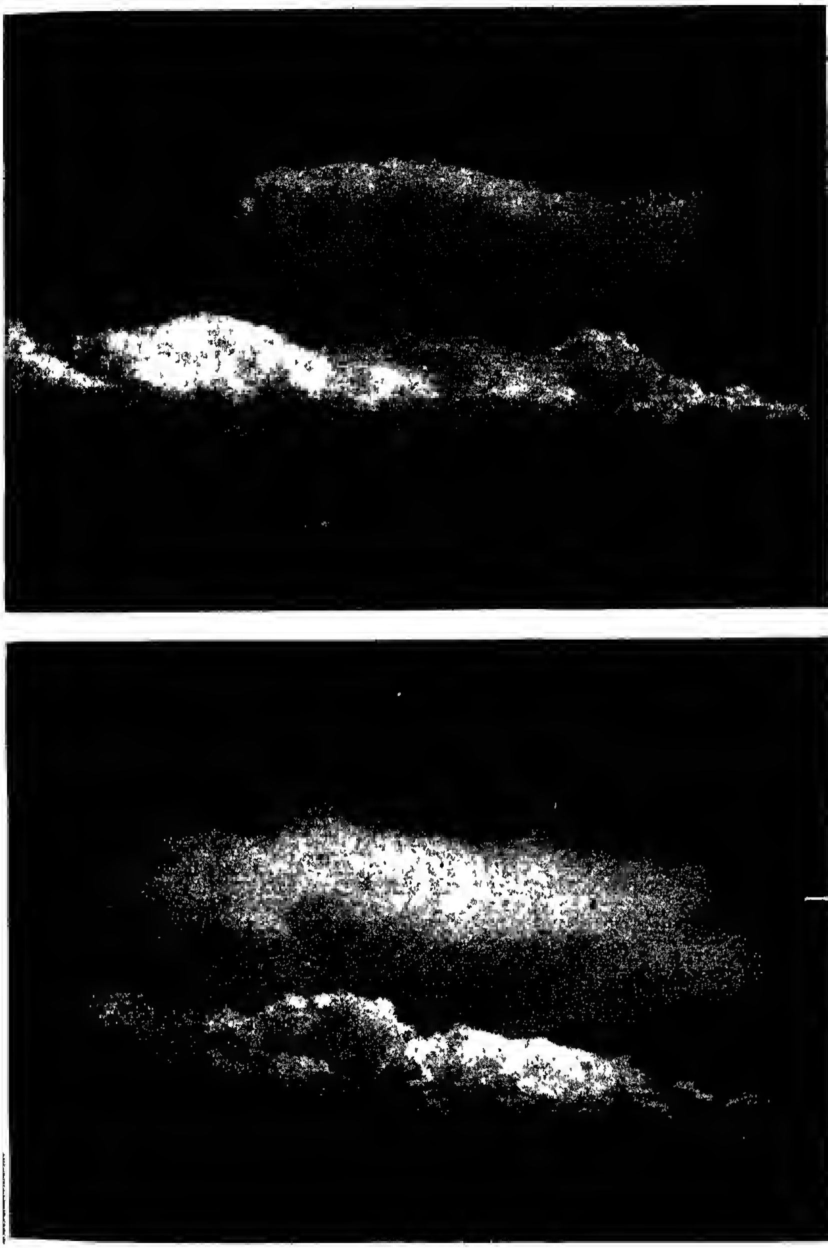


FIG. 26. Above. Local thundershower over New Mexico. Below. Same about thirty minutes later, showing shower at lower left. (R. E. Curtis photos)

FIG. 27. Day after day there are flat, fleecy clouds of fair weather in the middle of the day, and the drought continues (L W Humphreys photo)

eastward and it flows up the Mississippi Valley, over the Lake Region, and out to eastern Canada.

Thus there may be two kinds of droughts. The first occurs during periods when very little moist air comes into the continent. This is likely to happen in the winter season when the continent is much colder than the oceans and the winds blow outward from the continent. The second occurs more often in summer when the continent is very warm and the ocean is relatively cooler. Plenty of moist air flows into the continent, but it passes over and out to the ocean again, skipping around some areas and yielding little or no rainfall in the areas over which it passes. There are no masses of cool air to force the moist air upward to cause condensation and rain. Local heat showers occur here and there but the rainfall is small and widely scattered. It does not relieve the drought except in a few places.

In the Pacific Coast States, except in the mountains, it is dry every summer. The land is warm and the Pacific Ocean is not so warm. The air gets warmer as it blows inland instead of cooler. There are few local thundershowers or none at all. In winter the land is cold in Pacific Coast States, and the ocean is relatively warm. There is plenty of rain because the moist air gets cooler as it blows inland.

When this Pacific air blows inland and comes to the mountains it is forced upward and cooled. Much rain falls. As it passes over the mountains and starts down on the east side it gets warmer instead of colder and no rain falls. If it comes to a higher mountain range, there will be rain again but at a higher elevation. (Fig. 28.) Most of the moisture is taken out of the air on the west slopes of the mountains. No rain of consequence comes to the Great Plains, Central Valleys, and the eastern and southern part of the United States directly from Pacific air because it is robbed of its moisture in passing over the great mountain barrier. The moisture in this area must come from the Atlantic and Gulf.

But if we were empowered to rearrange the mountains in the western part of North America, we scarcely could improve on the plan adopted by nature. We would terrace them with the lowest elevations to the west and with increasingly high terraces toward the east so that each succeeding terrace would get rain at higher levels from the prevailing westerly winds. Finally, from our highest terrace we would drop abruptly to the plains so that the eddies

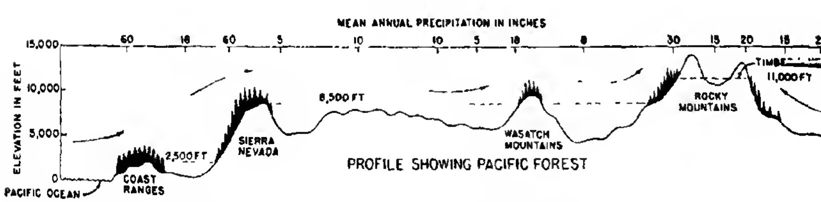


FIG. 28. Air moving from the Pacific Ocean eastward across the mountains near the 39th parallel is forced upward and as a result precipitation maintains forests on the Coast Ranges at an elevation of 2,500 feet. With further upward movement to the top of the Sierra Nevada at 8,500 feet, precipitation maintains forests on west slopes and on ridges, but on descent beyond into the Great Basin the air becomes dry. Farther eastward the Wasatch Mountains catch enough precipitation to support forests, and the Rockies in turn cause precipitation up to the timber line at 11,000 feet. On the east slopes of the Rockies the east and southeast winds from the Atlantic and Gulf bring precipitation. The mean annual precipitation in inches is shown across the top of the diagram. (After Raphael Zon)

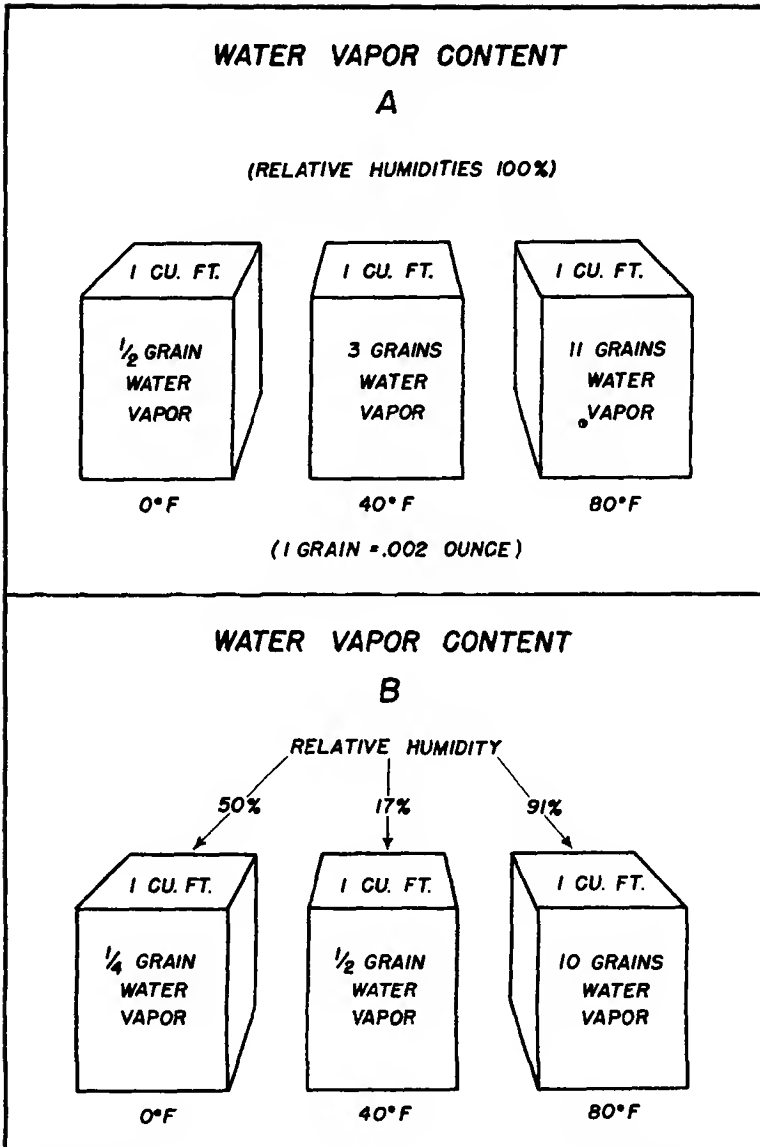


FIG. 29. Water vapor content of air. See explanation on opposite page. (Lorimor)

to the eastward of the mountains would draw moisture from the east and south. The mountains as we find them are terraced roughly in this manner.

There are years when the warm moist winds from the Gulf of Mexico and Atlantic Ocean blow inland to the very foothills of the Rockies; cold air masses get in the way and plenty of rain falls. The Great Plains and the prairie and range country in general have a wet year. At other times the moist air fails to reach the Great Plains. It is turned by the rotation of the earth and passes off to the northeast. At still other times the warm air is so directed that it reaches the Great Plains in spite of earth rotation, but it gets warmer and warmer. No cold air intervenes and there is no rain or only scattered showers.

What controls are at work to produce these different results in different years? We hesitate to accept the idea that this happens

FIG. 29 (page 64). The quantity of rainfall that can be obtained by cooling is illustrated by the diagrams in Figure 29. A cubic foot of air subject to three different temperatures (Section A in Figure 29) shows that at 0°F. only ½ grain of invisible water vapor can exist in a cubic foot, but if the temperature rises to 40°F., 3 grains of invisible water vapor can exist in that same cubic foot and at 80° F. there can be 11 grains of invisible water vapor in the same space. If any of these cubes are cooled appreciably, the water vapor is condensed out as visible water particles. If the 80° cube is reduced to 40°, the capacity of the space will be reduced from 11 grains to 3 grains and 8 grains of water vapor will be condensed. Cooling is the main process by which condensation and precipitation (fog, rain, snow, etc.) occur in nature.

In Section B of Figure 29 we have the same cubic foot samples except that they now represent drier conditions; that is, they do *not* contain all the water vapor possible at those temperatures. The cube on the extreme left has only ¼ grain of water present, which is only 50% of the amount that could be present (comparing with the same cube in Section A). The middle cube in Section B contains only ½ grain of water vapor as compared with 3 grains that could be present or only 17%. The same reasoning shows that the cube on the extreme right in Section B has 91% of the water vapor that could be present.

In Section B if the temperature of the 80° cube is reduced to 40°, the water vapor content will be reduced from 10 grains to 3 grains (see middle block of Section A) and 7 grains of water vapor will be condensed. If the 40° cube in Section B is reduced to 0°, no water vapor will be condensed. (See first cube in Section A)

on such a large scale just by chance. There must be a good reason, and the forces that control the movements of these vast air masses must be powerful ones.

In the preceding pages we have presented the problem. Next we shall look at the records and try to find the answer.

VI. WHY DOESN'T IT RAIN?

THE struggle of vegetation to find adjustment to the rainfall of the world has been going on for ages. Year after year the drought-resistant vegetation creeps forward with the advance of the rains, slowly building a protective covering over the prairies and ranges. Then comes a change in weather and it recedes. Hot dry winds and rainless cold winds prevail for a time, and the vegetation becomes thinned and loses ground year by year. In the dry intervals the soil is blown by hot winds.

The effect on vegetation is not altogether a question of rainfall. Temperature is an important factor in determining the amount of moisture needed for vegetation to flourish. In hot climates much of the rainfall is evaporated, and in cold climates less. There are other factors, such as the proportion of the rainfall that runs off without penetrating the soil. In classifying climates it is very difficult to get a proper measure of each of these several factors, so it is customary to use the vegetation itself as an indication of the effectiveness of precipitation.[17] The normal distribution of climatic types in the United States determined by the effectiveness of precipitation evaluated in terms of temperature is shown in Figure 30.

Figure 31 shows the percentage of normal rainfall by states in a very wet year (1915) and in a great drought year (1934). While these years represent extremes on a national scale, there were several states with above-normal rainfall in 1934 and several with below-normal rainfall in 1915. The differences in climatic types for these two years (Fig. 8) show mainly a great expansion of arid climate in 1934 as compared with 1915, while the humid climatic subdivisions as a whole were reduced in area in 1934.

Figures 32 and 33 show the average rainfall in the ten driest and ten wettest years in the forty-year period from 1899 to 1938. In

[17] The classification mentioned here is C. W. Thornthwaite's as described in the *Atlas of Climatic Types in the United States, 1930-1939*. Washington, 1941.

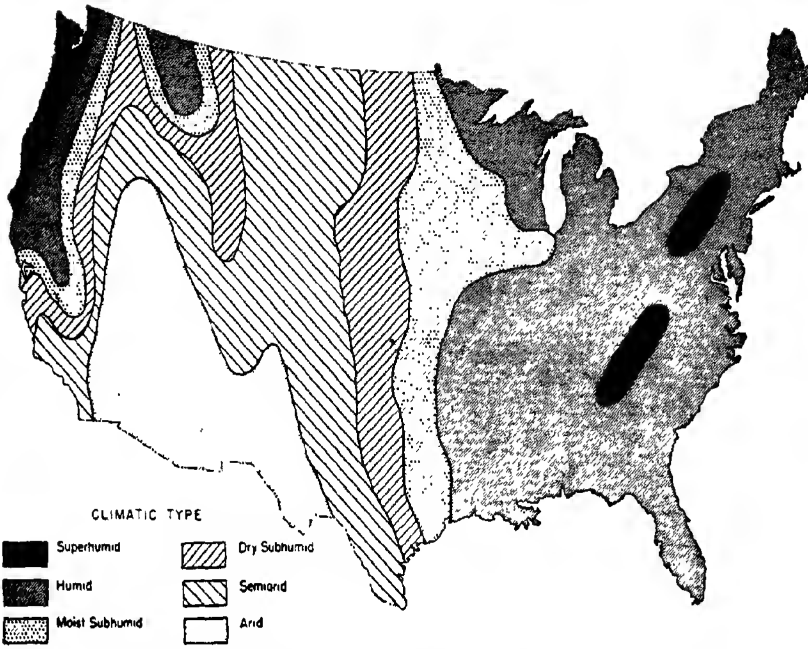


Fig. 30. Generalized normal distribution of the principal climatic types in the United States. See also Figure 7. (Thornthwaite)

these maps and in Figures 7 and 30 we see rainfall lines and climatic boundaries tending to run north and south, with some irregularities. In each case the climate becomes less humid as we proceed from the Atlantic westward to the Rockies and also from the middle and northern Pacific Coast eastward into the mountains. The influences of the Atlantic and Pacific as sources of moisture are clearly evident.

When we draw lines (isohyets) through places having equal rainfall as in Figures 32 and 33 we see that in the ten wettest years and the ten driest years the lines show about the same pattern. In maps of this type we could change from wet years to dry years by merely changing the figures at the ends of the lines and the generalized picture would not be far wrong. The important point is that when we have a dry year the rainfall for the country as a whole diminishes and the lines of equal rainfall east of the Rockies remain in about the same pattern but move toward the Atlantic. For example, in Figure 33 the line for 30 inches runs

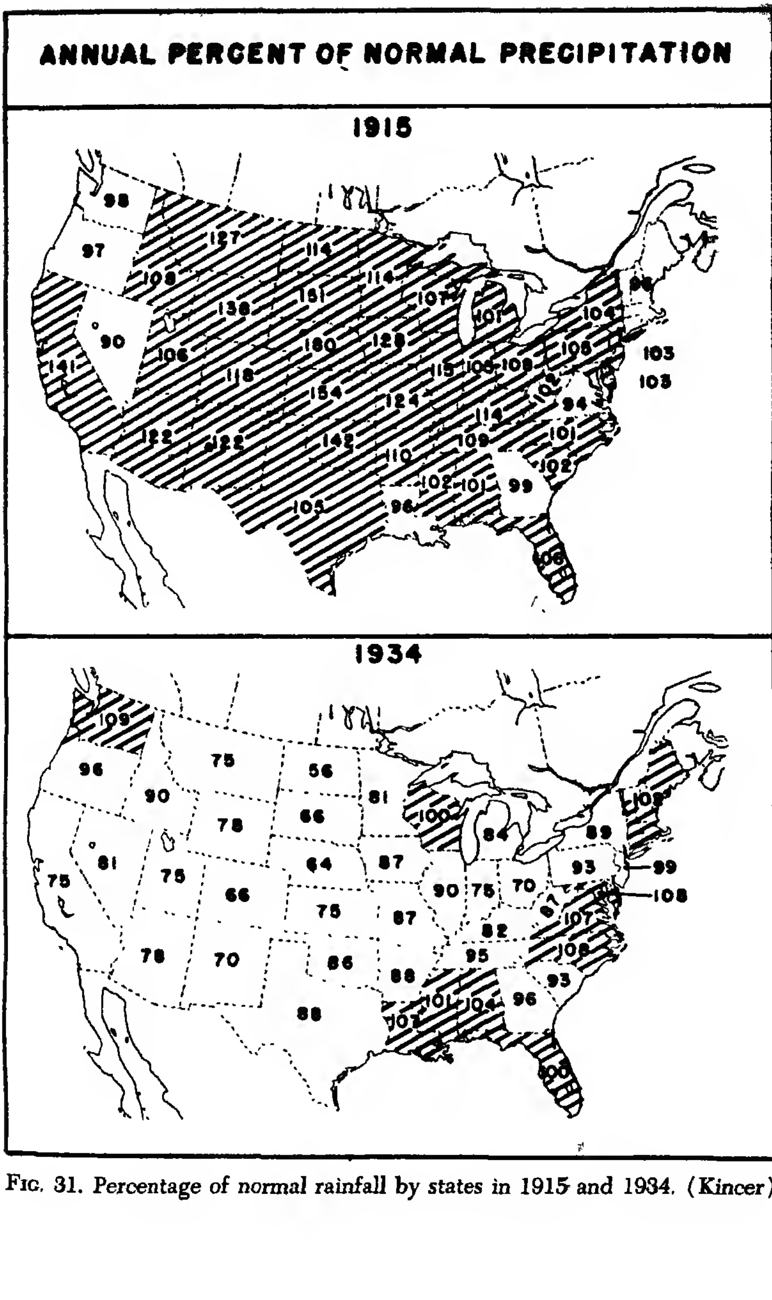


Fig. 31. Percentage of normal rainfall by states in 1915 and 1934. (Kincer)

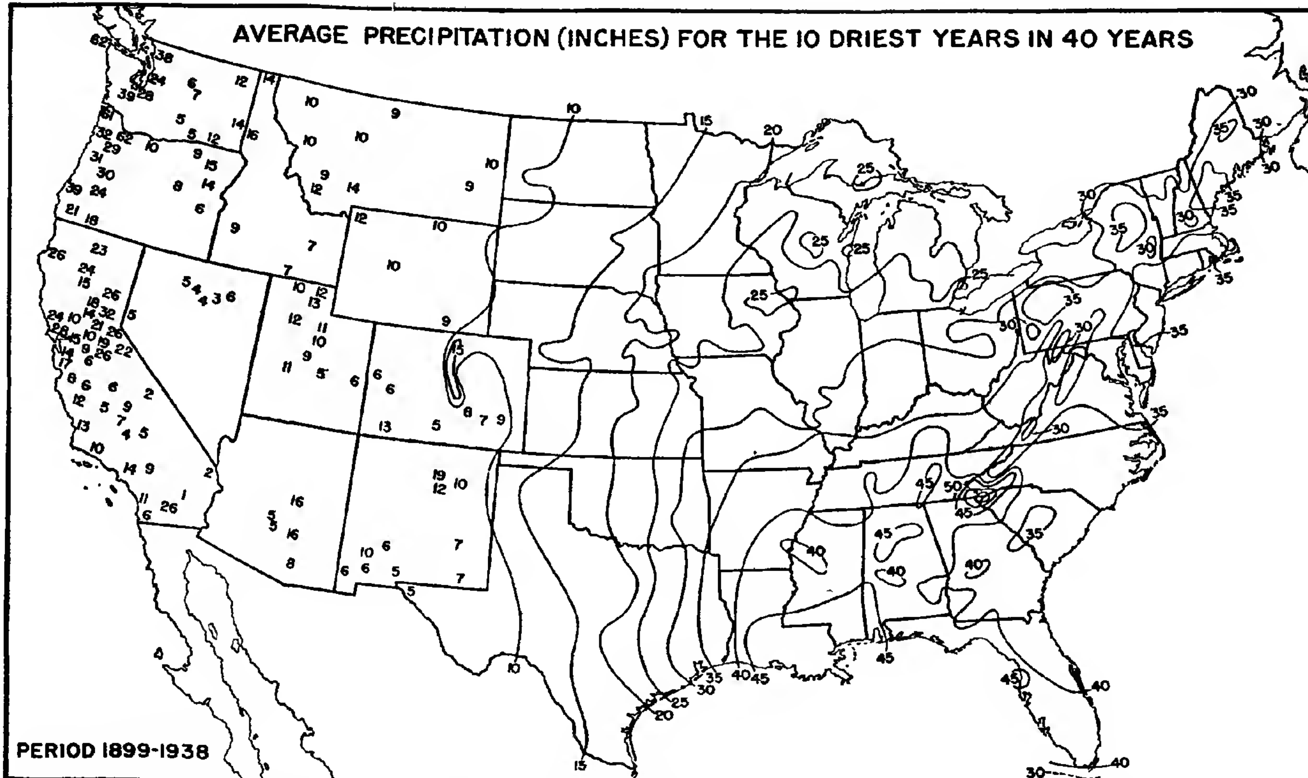


Fig. 32. Average precipitation (rain and melted snow) in the ten driest years in the United States in the 40-year period from 1899 to 1938.

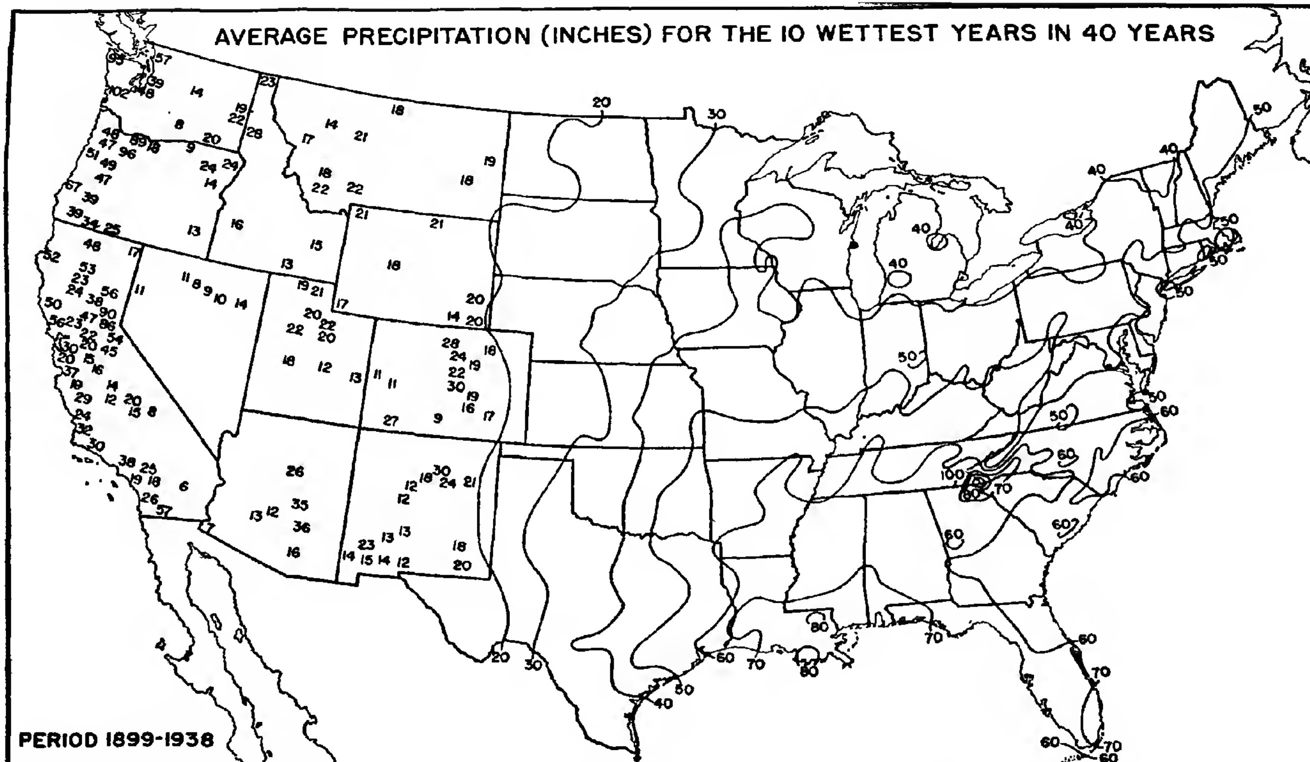


Fig. 33. Average precipitation (rain and melted snow) in the ten wettest years in the United States in the 40-year period from 1899 to 1938.

from northwestern Minnesota to southwestern Texas while in Figure 32 the line for 15 inches is in approximately the same position.

Though this pattern causes us to suspect on first examination that the condition of the oceans has a great deal to do with deficient rainfall in the dry years, it is not clear at once just how the deficiency is brought about. Did less water vapor come into the continent in the dry years or did it come in as usual and fail to be precipitated? The usual method of seeking to find the causes of general droughts and floods is to study daily weather maps to see why it rained or failed to rain in each situation and then attempt to generalize on these several cases. But the rainfall for a year is made up of seasonal changes which introduce complications. There are several maps each day, and for a year the number of maps runs into the hundreds. This method has failed to reveal the basic controls which determine that the year as a whole will be persistently dry.

There is another fundamental objection to the method of studying droughts by using daily weather maps. It is not practicable to project our findings into the future. To do this, it would be necessary to have in mind a similar series of weather situations and daily maps for the coming year and attempt the bewildering and nearly impossible job of computing or estimating the effects of these combinations of daily weather situations on the weather of the coming year as a whole.

We shall deal with annual amounts of rainfall averaged for the United States as a whole and see if the causes of deficient rainfall can be determined on that basis. Later we shall consider monthly and seasonal averages if the results of our studies of annual amounts warrant it.

There is always plenty of moisture in our atmosphere and a certain amount of it is sure to fall to the earth as rain. But there are times when it persists in falling in what we consider to be the wrong place. For example, in some bad drought years the moisture skips the plains and is carried over to eastern Canada. In the years from 1886 to 1930 the five worst national drought years were 1910, 1917, 1924, 1925, and 1930. In the same period the five

wettest years in the United States were 1905, 1906, 1915, 1919 and 1927. In these five dry years in the United States, Montreal averaged 42.11 inches and St. Louis 30.86 inches. In these five wet years in the United States, Montreal averaged 38.90 inches and St. Louis 42.99 inches. In other words, in wet years in the United States, St. Louis had 4.09 inches more than Montreal and in dry years St. Louis had 11.25 inches less than Montreal. It appears that the moisture that might have fallen at St. Louis in the dry years was carried up into Canada before it became sufficiently cool to precipitate. In our wet years enough moisture was removed from the air in the United States so that Canada had a decrease in rainfall.

At North Platte in western Nebraska the comparison of rainfall amounts tells the same story. There was a difference of 13.31 inches between North Platte and Montreal. North Platte has an average annual rainfall of only 18.57 inches, hence this swing of more than thirteen inches between Montreal and western Nebraska can be the difference between prosperity and disaster in the Great Plains. Of course we cannot prove the case by rainfall records in two or three localities, but these figures give an idea of the magnitude of the swing in the distribution of rainfall in the area east of the Rockies.

As we have seen, the rotation of the earth tends to carry moist Atlantic and Gulf air away from the Great Plains. Powerful forces are necessary to control these currents in such a way that the rains reach the plains in good years in spite of the rotation of the earth. On the other hand, we may assume that rain is the normal condition and that in the drought years in the Great Plains, the rains were diverted by some gigantic atmospheric force. What is it and how does it act?

For the time being, there is no way of finding the answer except by running through the year-to-year weather records over and over again looking for a clue. We have fifty-nine years of national weather records to examine.

We must always keep in mind that air over the continent changes temperature readily from season to season, while over the oceans the temperature changes more slowly. The high specific

heat of water and its greater mass per unit volume than land are important factors. Some of the sun's rays are not very effective in heating the ocean. Short rays penetrate the water and some of the energy is spent in heating it below the surface. The waters of the ocean are constantly being mixed by strong winds, preventing the formation of a shallow layer of warm water at the surface. The result is that the heat of the sun must raise the temperature of a lot of water before the upper layers of the ocean get much warmer.

On the other hand, land heats more quickly. It absorbs the sun's heat but the rays heat the surface without penetrating very far into the earth. Land is a better radiator of heat than is water; hence land cools more rapidly. This causes the continents to be warmer than the oceans in summer and colder in winter. The oceans act as great stabilizers preventing the atmosphere above them from changing temperature except very slowly.

Let us examine the fifty-nine years of national weather records. The moist air currents from the Atlantic and Gulf move across the United States, swinging back and forth from season to season and year to year. High and low pressure systems in endless succession cross the country. For a time they move far to the south, then along the Canadian border, then the lows go back to the south again. The rain areas expand, move, and disappear. There are years with deficient rainfall, and the picture changes. Rain comes more frequently. In all of this there is a strong suspicion that the Atlantic Ocean and the Gulf of Mexico cause local and rather brief droughts in eastern and southern United States. Spring comes with cool Atlantic waters and rapidly rising temperatures over the continent. The moist air from the Atlantic gets warmer as it moves inland and there is little or no rain. This sometimes makes a brief drought. But the relatively cool Atlantic waters along the east and south coasts get warmer as the season advances and soon there is rain.

Again, when there is a persistent outflow of air from the continent to the ocean, which happens most often in winter, there is little rain. But this also is a temporary condition.

When we consider the big droughts affecting nearly all of the country, there is no consistent and dependable indication that

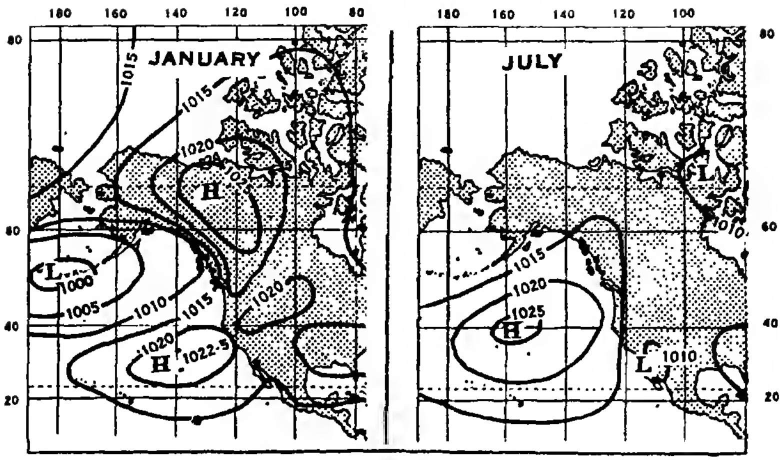


Fig. 34. The Pacific high in January and July (pressure in millibars). In January the high (H) is small and there is a low over the Aleutians (L) and another high (H) over the interior of Canada. In July the Pacific high (H) is expanded and located farther to the northwest.

either the Atlantic Ocean or the Gulf of Mexico is responsible. Meteorologists have spent a great amount of time for the last seventy-five years in a search for the clue in Atlantic and Gulf conditions.

It is important always to notice the pressure of the atmosphere. Air has weight. We measure its weight with a barometer. When there is more air over us, the barometer is higher and when there is less air over us the barometer is lower. We write the word "high" on the weather map in the center of areas where the barometer is higher than in surrounding areas, and we write "low" in the center of areas where the barometer is lower. In addition to the highs and lows which continually appear and move across the country and disappear, there are other highs and lows which remain from month to month in about the same positions. In the latter class we see in the eastern Pacific Ocean a fairly permanent area of high pressure. (Fig. 34.) In winter, when the continent is cold and the Pacific relatively warm, this high is small and far to the southeast. As summer comes and the continent becomes hot and the Pacific is not nearly so warm as the continent, the Pacific

high expands and the pressure rises. It extends to the north and west; then as winter comes again the high shrinks back to the southeast near the coast of Southern California.

We notice that in the colder part of the year, when the high is small and located in the southeastern part of the ocean near California, there is plenty of rain in Pacific Coast States; but in the warmest part of the year when the high is extended to the north and northwest, there is always a drought in Pacific Coast States. This change takes place every year. Certainly the Pacific Ocean is responsible for winter rains and summer droughts in Pacific Coast States. If the Pacific Ocean should change its temperature as rapidly as the land, it would be as likely to rain in summer as in winter on the Pacific Coast. Clearly it is this resistance of the Pacific Ocean to temperature change that causes these rainfall variations on the West Coast.

But can the Pacific Ocean have anything to do with droughts in the Great Plains? There is a series of high mountain barriers between the Pacific and the Plains which seems to isolate them from each other. There is little rain in the Pacific States in summer, but there is rain east of the Rocky Mountains. From the weather maps we can easily see that rainfall east of the Rockies comes from the Atlantic and the Gulf of Mexico. The courses of storms and heavy rains are clearly plotted. It seems preposterous that the Pacific Ocean should cause droughts east of the Rockies

There are other arguments to consider. The Pacific Ocean is the largest body of water in the world. It dominates our hemisphere, lying to the west, and southwest of the United States. Even going due south from Key West, Florida, you come eventually to the Pacific off South America. Also we know that the prevailing atmospheric circulation in our latitudes is from west to east, from the Pacific toward the United States. (Fig. 68.)

Let us look again at the fifty-nine years of weather records (Figs. 35, 41, 43, 48), giving special attention to the Pacific high pressure area. A national dry year goes by, and we see that the Pacific high is more expanded than usual. Another dry year, and the Pacific high is expanded again. In almost every national dry year, the Pacific high pressure area is expanded. (Fig. 35.) It

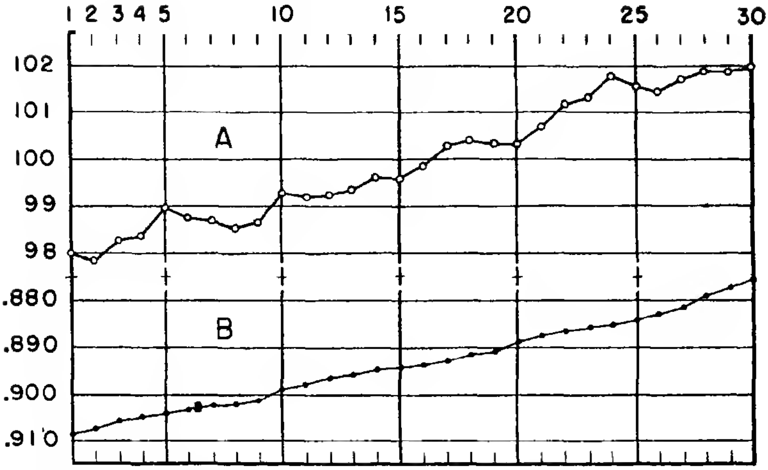


FIG. 35. For this diagram, Portland, Oregon, is used as a key point in the Pacific Northwest. When the Pacific high expands, the pressure increases along the coast to the northward (*See Figure 38*) and when *it* retreats, the pressure on the north coast becomes relatively low. In computing this diagram, the 59 years from 1886 to 1944 were first arranged in order of the annual station barometer readings at Portland, that is, the year with the highest average pressure first, the next highest second, etc., to the lowest, last. Running 30-year means of national rainfall and Portland pressure were computed for these 59 years arranged in this order. This gives thirty 30-year means. The national rainfall is shown at A and Portland pressures at B. The pressure scale is reversed because high pressure attends deficient rainfall, and vice versa. The pressure values shown by the scale at the left are to be added to 29.000 inches, e g., .910 is 29.910. This shows that the very small variation of about .035 inch in pressure is associated with a national rainfall variation of about 4%. Scale of years is shown at the top of the diagram.

occurs too often to be a mere coincidence; surely we should be suspicious.

But the wet winds that bring rain to the Great Plains come from the Atlantic and the Gulf of Mexico. Perhaps the Pacific Ocean exerts some mysterious control over these winds. Cold winds from Canada are necessary to cause *rains* on the Great Plains; perhaps the Pacific exerts control by way of these Canadian winds. The subject requires further investigation. We seem to have a footprint of the monster which causes droughts. Is the Pacific Ocean a monster lurking in our own back yard?

VII. THE MONSTER IN THE BACK YARD

When compared to the great stretch of oceans from the east coast of Asia to the west coast of Europe, the continent of North America seems to be little more than a large island. The prevailing west-to-east winds of the Northern Hemisphere sweep across this vast sea area, powered by the sun's heat and modified by the changing seasonal contrasts between continent and oceans In its broad features, the climate of North America is dominated by the influence of the oceans, primarily the Pacific Ocean. This great body of water resists every widespread change in temperature that tends to develop in the United States. The Pacific Ocean has a tremendous regulating power over the atmosphere, and in our latitude this power is applied to the eastward in the direction of the normal circulation of the atmosphere.

The circulation of the atmosphere results in the development of a cold ocean current off our Pacific Coast—the California Current. The winds over the surface of the oceans north of the equator cause a drift of water which in our latitudes is toward the north and east in the western and northern parts of the oceans, and toward the east and south in the eastern parts of the oceans. (Fig. 36.) Off the Pacific Coast of the United States the surface waters of the California Current move southward along the coast During part of the year there is much upwelling or overturning which brings cooler water from the depths to the surface of the ocean. The southward movement brings cooler surface waters from higher latitudes, and the stronger current produces lower temperatures. There are many complications, but the final result is that the water is relatively cool off our west coast. The temperature of the water seems to vary from year to year depending on the strength of ocean winds and the movements of waters which it causes.

The variation of surface water temperature from winter to summer in the open ocean off the west coast of the United States is less than ten degrees. At San Francisco, the variation in air

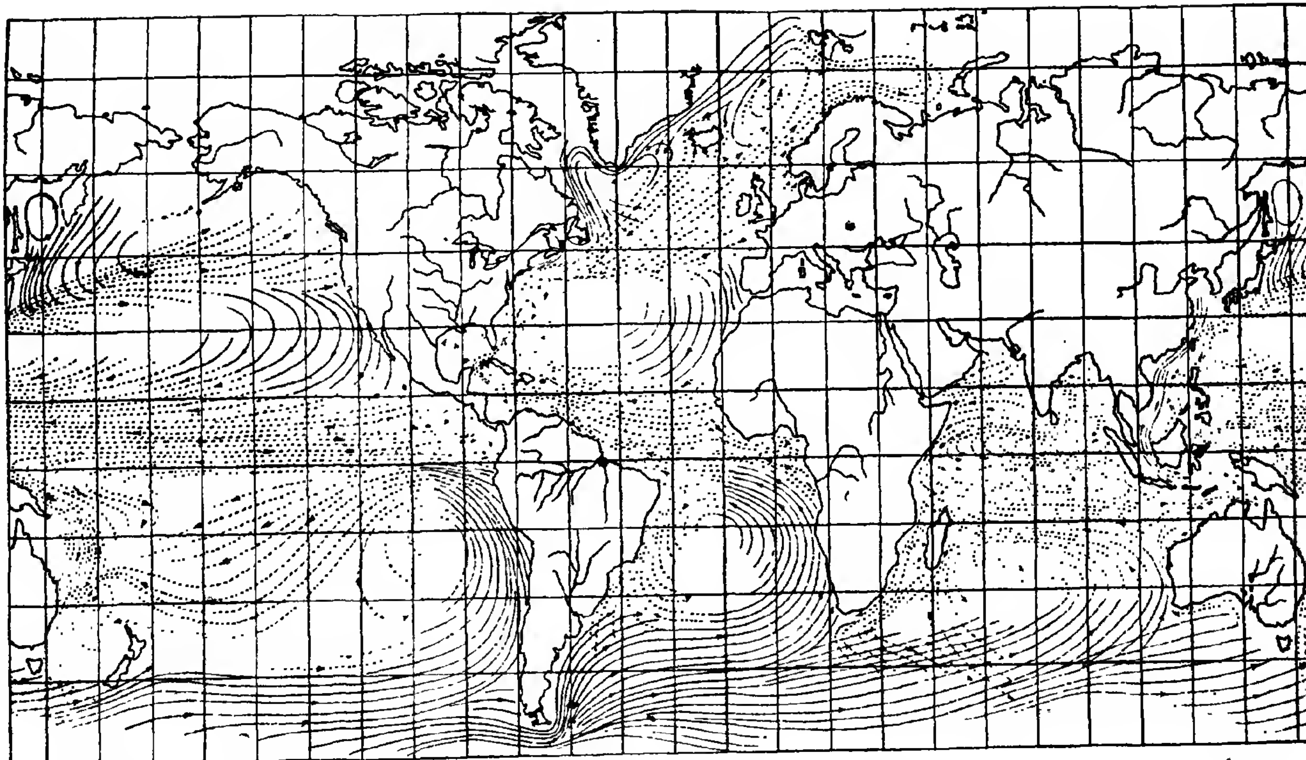


Fig. 36. Ocean currents. Cold currents, solid lines; warm currents, dotted lines. Arrow heads indicate direction of movement of water.

temperatures between mid-winter and mid-summer is about 8°; at Portland, 18°; at San Diego, 14°. In the interior it is larger, for example, 26° at Red Bluff, California. These summer-winter differences near the Pacific compare with 47° variation at St. Louis, Missouri, and 60° at Bismarck, North Dakota. The temperature at San Francisco, especially, shows the regulating effect of the Pacific on coastal air temperatures. The temperature varies only from 57° in July to 49° in January.

We know something about the average temperatures of the surface waters of the Pacific and the normal changes with the seasons, but very little is known about the irregular changes from year to year. Temperatures recorded along the coast give some indication, but there is a great deal of uncertainty. The direction of the wind has an important effect. Cloudiness and rainfall also affect the temperature of the surface air. Therefore, in dealing with this problem of Pacific Ocean temperatures in relation to rainfall in the United States, we must depend on vague generalities and deductions from temperatures of the air and water along the coast and especially on the pressure of the atmosphere (barometer readings) and the changes in wind and rainfall.

For the most part it is a question of *relative* temperature. We say that the Pacific is warm in the winter and cool in the summer. That is true only with respect to the land temperatures. When the land gets hot in summer the Pacific remains relatively cool, and when the land gets cold in winter the Pacific is relatively warm. The ocean resists temperature changes. By thermometer measurements, the Pacific surface waters off our west coast are about 10° cooler in winter than in summer. They only seem warm in winter and cool in summer by contrast. (Fig. 37.)

Let us examine the weather records again. Figure 38 shows the average *differences* of pressure by months between Portland, Oregon, and San Diego, California. Where the curve is positive, Portland's pressure is relatively higher; where the curve is negative, San Diego's pressure is higher. Here we see that when the Pacific high expands in the warm season, Portland's pressure becomes higher than San Diego's; and in the cold season, when the Pacific high shrinks toward the south and east, San Diego's pressure is

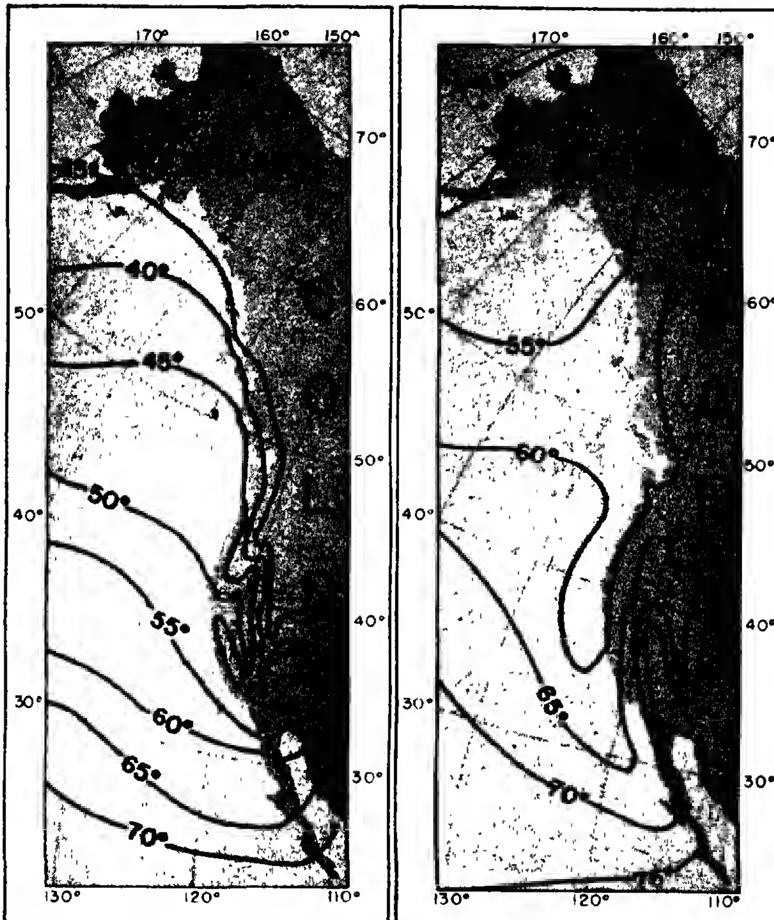


FIG. 37. Average temperatures along west coast of North ~~America~~ and North Pacific Ocean. Left, in February. Right, in August.

higher than Portland's. The pressure at Portland is an indication of the development of the Pacific high.

We shall use as a test the barometer readings at Portland, Oregon, averaged for the fifty-nine years from 1886 to 1944. (See Figure 35.) These barometer readings represent the average for

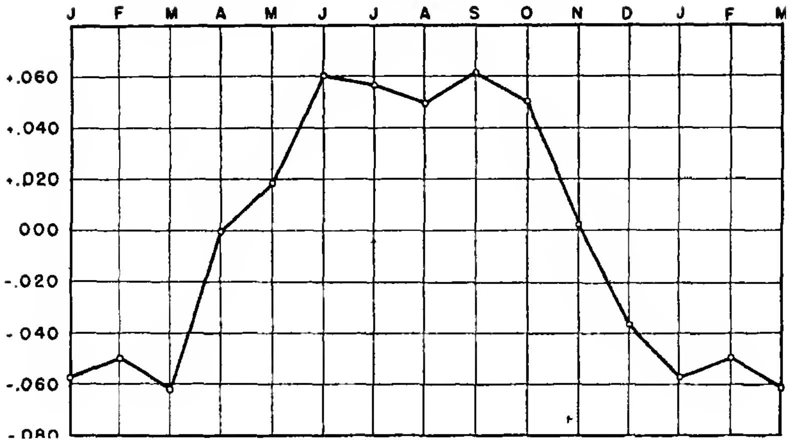


Fig. 38. Normal difference in pressure between Portland and San Diego by months. Positive values show Portland pressure relatively higher than San Diego pressure and vice versa. When the Pacific is relatively cool and the high expands in the warm season, the pressure is relatively high at Portland; and in winter when the Pacific is relatively warm, Portland pressure is relatively low.

each year. For example, the average at Portland for 1888 was 29.885 inches.[18] Since the first two figures are always 29, we shall use only the last three (thousandths of an inch). We have also the average rainfall for the entire United States for each of these years from 1886 to 1944. These figures are given in the Appendix by months and years.

The rainfall for the entire United States (including melted snow measurements) is taken from the averages for all the states, each being weighted according to the area of the state. (See Appendix.) The average for the United States as a whole is about 29.10 inches of rainfall each year. The wettest year from 1886 to 1944 was 1905 with 32.79 inches, and the driest was 1910 with 24.63 inches. At first thought this does not seem to be much of a difference; but when the rainfall for the United States as a whole falls as low as 25 or 26 inches, it is a very serious matter. There are large areas that receive barely enough rainfall in good years,

[18] These readings are fully corrected but not reduced to sea level.

and a national deficiency of 10% to 15% is sure to mean disaster in some areas, especially if it continues for two or three years. Kincer[19] calculated for the drought of 1930 that for the eight states—Maryland, Virginia, West Virginia, Kentucky, Ohio, Missouri, Indiana, and Illinois—which were most affected by the drought, the shortage of rainfall was nearly three hundred billion tons; and, in general, for each 100-acre farm for the three summer months of 1930 alone, the shortage was sixty thousand tons, or an average deficiency of nearly seven hundred tons of water a day!

In Figure 39 on Curve B the national amounts of rainfall for each year have been expressed in percentages of the normal. For example, 1905 had 32.79 inches which was 113% of the normal, and 1910 had 24.63 which was 85% of the normal.

The records show that in the five years with the highest barometer at Portland (1910, 1917, 1924, 1928, 1929) the national rainfall averaged 26.99 inches; in the five years with lowest barometer at Portland (1902, 1904, 1915, 1940, 1941) the national rainfall averaged 30.56 inches. The persistence of this condition is illustrated by the fact that in the five years succeeding those with high barometer at Portland (1911, 1918, 1925, 1929, 1930) the national rainfall averaged 28.02 inches; and in the five years succeeding those with low barometer at Portland (1903, 1905, 1916, 1941, and 1942) the national rainfall averaged 30.90 inches.

On the other hand, in the five years with greatest national rainfall (1905, 1906, 1915, 1919, and 1941) the barometer at Portland averaged 29.866; in the five years with least national rainfall (1910, 1917, 1930, 1934, and 1939) the barometer at Portland averaged 29.918. It was consistently higher in the dry years and lower in the wet years. These differences in the barometer readings seem small, but they are averages for the entire year, and even such small variations are extremely important.

The diagram (Fig. 39) shows at A the average barometer reading at Portland each year from 1886 to 1944 (smoothed) and at B the national rainfall (smoothed). The scale for barometer readings at A has been reversed because the two generally vary in the

[19] Kincer, J. B., "The Drought of 1930." *Bulletin of the American Meteorological Society.* January 1931.

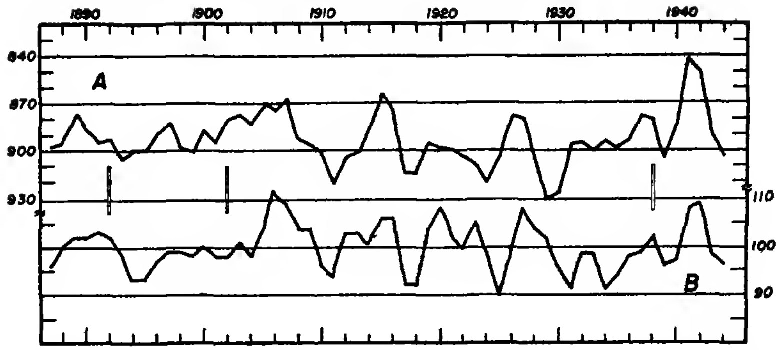


FIG. 39. A. Yearly means of barometer readings (station level) at Portland, Oregon, in thousandths of an inch over 29 inches, smoothed by formula $\frac{a+b}{2} = b'$; B. Yearly rainfall for entire United States smoothed in same manner. For example, value plotted for 1887 is mean for 1886 and 1887, etc. Short bars in middle left and middle right of diagram show where barometer was moved to a new location, but all readings were reduced to the standard plane of reference.

opposite sense; that is, high barometer corresponds to low rainfall, and vice versa.

Of course, Portland gives only an indication of Pacific air pressures, but there seems to be a definite relation between Portland barometer readings and national rainfall, at least so far as major oscillations are concerned. This is evident in Figures 35, 39, and also in Figure 40, which shows average station pressures in the very wet decade in the United States, 1906 to 1915, and in the very dry decade, 1930 to 1939. In Figure 40 we see below-normal pressure in the region extending inland from Portland in the wet years, and above-normal pressure extending inland in the region near and east of Portland in the dry years.

We must not depend too much on mere correspondence of two series of events like the barometer readings at Portland and national rainfall. It is a characteristic of weather data that they show such agreements for a period of years, and then the agreement fails for a period of years, perhaps to come into agreement again at a later time. The agreement between Portland pressures and national rainfall proves nothing unless we can show what

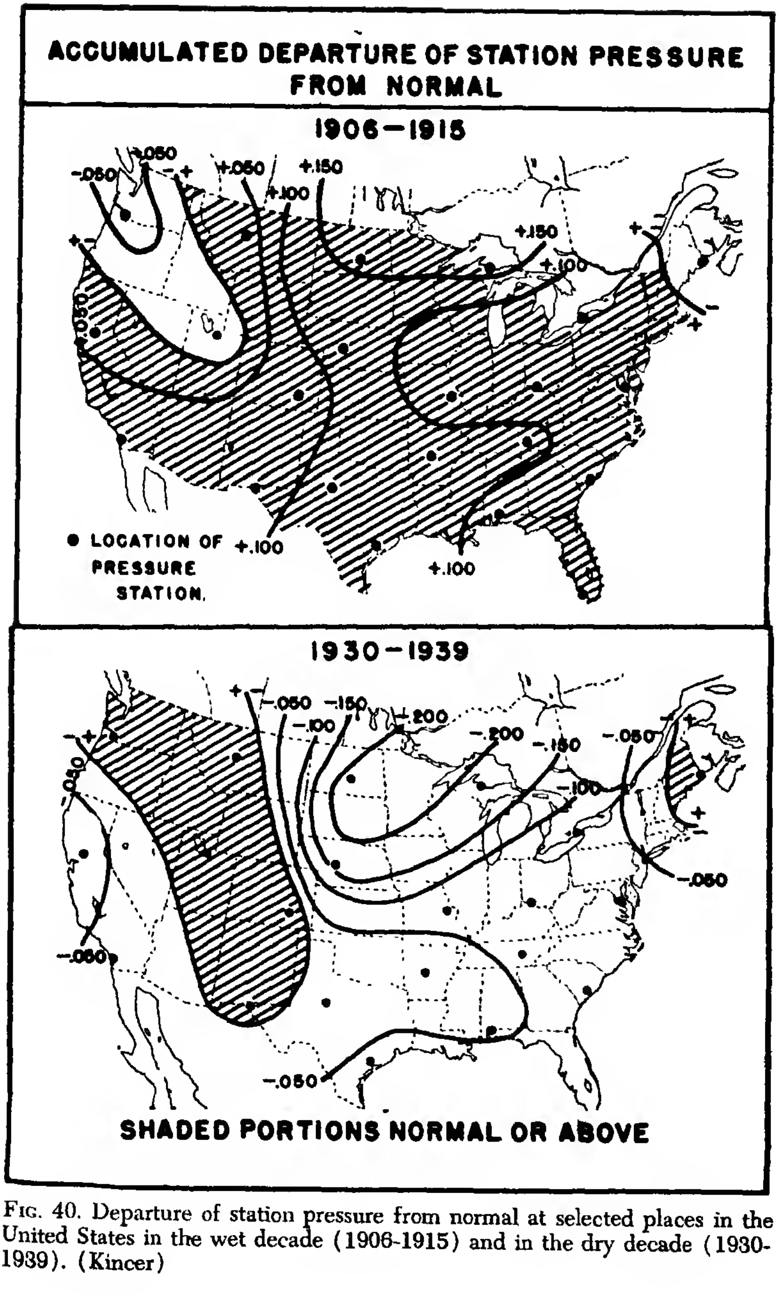


FIG. 40. Departure of station pressure from normal at selected places in the United States in the wet decade (1906-1915) and in the dry decade (1930-1939). (Kincer)

actually takes place to influence both the national rainfall and the Portland pressures.

One suspicion should be recorded. The North American desert is located in southwestern United States and Northwestern Mexico where there are relatively cool waters to the westward and where temperatures over the land in winter seldom fall low enough to make the nearby ocean *relatively* warm. In the North, however, the land becomes cooler than the ocean, and in Oregon, Washington, and British Columbia there is much more winter rain than in San Diego.

FIG. 41. Locations of places mentioned frequently in the text.

At this point it is interesting to note that there is a desert on or near the west coast of every continent between 20° and 30° of the equator, both north and south, and that every one of these coasts has a cold ocean current (Fig. 7) and a high pressure area to the westward.

High pressure goes with low temperatures, and there is now a suspicion that a relatively cold Pacific causes our desert areas to expand and tends to reduce the rainfall over the nation as a whole,

except perhaps in the interior of the Northeast and, as previously noted, in eastern Canada as shown by the records at Montreal.

The records show that in the nine national dry years from 1886 to 1930 with less than 95% of normal rainfall, our three key Pacific cities,[20] Portland, San Francisco, and San Diego, had lower average temperatures than in the ten national wet years with rainfall more than 105% of normal. This is nothing more than an indication, however, for temperatures at places near the coast are affected by wind direction, cloudiness, rainfall, and other factors. Nevertheless we may strongly suspect that the Pacific Ocean is the monster in the back yard which seems to control our national rainfall, exerting a power that is second only to the sun itself. We must now look at the underlying processes by which moist air currents and rainfall are controlled.

[20] The locations of places mentioned in the text are shown in Figure 41.

VIII. THE DROUGHT COMES OVER THE MOUNTAINS

THERE are great mountain ranges extending roughly from north to south in the western part of North America, and most of our rain falls east of these mountains. Therefore, if the Pacific Ocean controls rainfall, it must exercise this control in the upper atmosphere where the air passes over the mountains.

The atmosphere is a mixture of gases which become more and more tenuous with increasing height above sea level. Water vapor is one of these gases. Consequently there is much more water vapor at low levels than in the high atmosphere. Most of the action which produces rainfall must take place in the lower part of the atmosphere where there is plenty of moisture.

The atmosphere seems deep when we look up into the sky or take a trip in an airplane. But in fact more than half of the atmosphere lies below a height of four miles. If the atmosphere at all levels were equal in density to that at sea level, it would be only five miles deep. When compared with the breadth of North America this is very shallow. We must keep this in mind, because most illustrations show the depth of the atmosphere greatly exaggerated.

There is no upper surface of the atmosphere as there is of a body of water. The air simply gets thinner and thinner until it is almost non-existent at a height of 100 to 150 miles. Meteors and auroras show some exceedingly rare atmosphere at heights of 150 to 500 miles, but this thin upper air may be disregarded in the study of drought.

Even though the atmosphere has no upper surface, it may be said to expand or contract with changes in temperature. In summer over the continents it is expanded upward with high temperature, and in winter it gets cold and shrinks downward. This also happens when air moves across a warm or cold surface. For ex-

ample, when air moves long distances over a warm ocean it takes on the temperature of the ocean surface. When it leaves the ocean and crosses a cold continent in winter, it shrinks to lower levels as it becomes colder, and then there is less air at higher levels. The reverse occurs when air moves from a cold ocean to a warm continent; it expands upward as it passes over the warm continent, and the amount of air increases at high levels.

This happens in the case of North America and the Pacific Ocean. In winter the air over Canada and Alaska becomes colder and more dense and lies nearer to the ground. This leaves less air in upper levels over these areas, and we have what we may call a "sink." Over the ocean to the westward the air is warm and expanded and there is more at high levels than over the land to eastward. We may say that there is upwelling over the ocean. The air at upper levels over the ocean flows rapidly over the mountains into the continental sink. It piles in on top of the cold continental air, and the total amount of air over Canada and Alaska increases while the total amount of air over the ocean to the westward decreases. This takes place mostly in the north because the contrast between ocean and continental temperatures is greater in the north. The main sink is over Canada and Alaska.

The reverse action takes place between North America and the Atlantic. In winter the air passing out over the Atlantic becomes warmer and piles up at high levels. This reduces the motion of air in the upper atmosphere from the continent to the Atlantic. If it were water we would say that it has to be forced up hill. The prevailing motion of the air aloft is from west to east at all seasons. In winter air is moving rapidly into the continent in the northwest and slowly out of the continent in the northeast. This continues until the pressure in Canada is much greater than in the United States, and cold air is forced southward into the United States. This cold air offers an obstruction to the flow of warm moist surface air from the south. The warm air is forced up over the cold air, and there is rain or snow in the United States. When conditions are favorable, the same process goes on at other seasons. It is a question of the relative temperatures of the Pacific, the continent, and the Atlantic. This wintertime atmospheric flow

at high levels is shown pictorially in the right hand section of Figure 42.

As air flows from the North Pacific to Canada and Alaska, and the total amount of air over the northeastern North Pacific becomes less, air flows northeastward and northward from ocean areas to the southwest and south and this in turn tends to reduce

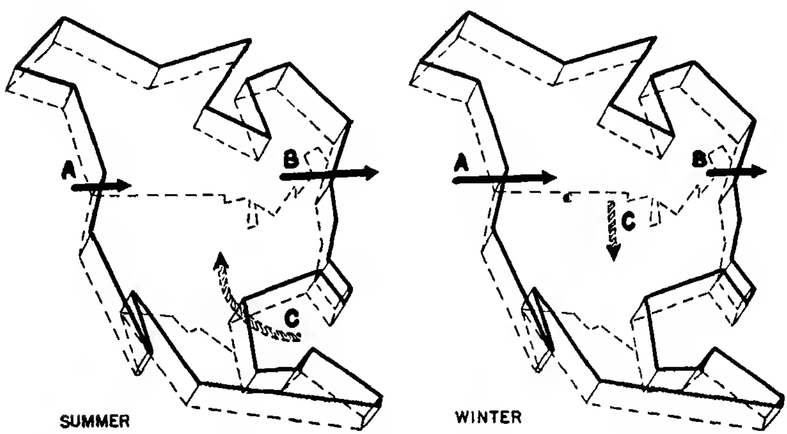


Fig. 42. Diagrams showing main components of air currents affecting rainfall. Dashed lines represent surface outline of North America; solid lines represent upper level in atmosphere. At left, the short arrow A indicates slow movement of air into the continent in summer; the long arrow B indicates rapid movement of air out of the continent to the relatively cool Atlantic in summer; and arrow C shows surface air flowing into continent to make up for the inequality of components A and B. At right, the long arrow A indicates rapid movement of air into the continent in winter; the short arrow B indicates slow movement of air out of the continent to the Atlantic in winter; and arrow C shows the north-to-south movement from Canada to the United States caused by the inequality in components A and B.

the amount of air over the entire eastern North Pacific. Consequently, the Pacific "high" becomes small and is located far to the southeast.

After the accumulated air over Canada has moved down into the United States, the difference in pressure is relieved temporarily. There is an interval during which the new air over Canada, dry and clear from its down-settling from upper levels, is becom-

ing cold by radiating its heat. In the meantime warm air is accumulating over the nearby Pacific as air arrives from ocean areas farther to the south and west. Continental air again sinks to lower levels and Pacific air at higher levels again flows down into the Alaska-Canada sink. The cold surface develops a sink and the warm surface an upwelling. In winter this increases the air pressure in Alaska and Canada and later in the United States and reduces it in the Pacific off our West Coast.

The accumulation of air in the northern continental sink naturally takes place more frequently in winter than at other seasons. It produces a north-to-south flow of dry cold air in winter from Canada into the United States. It appears that these cold air masses from Canada are more frequent when the Pacific is relatively warmer than usual or the continent relatively colder than usual in the far north, and the overflow from the Pacific upwelling across the mountains into the Alaska-Canada sink is more rapid than usual. When strongly developed this causes cold waves and blizzards in our Middle West sometimes extending to the Atlantic and Gulf coasts.

When the Pacific is not so warm or the continent not so cold, the overflow is weak and the north-to-south movements of cold air masses from Canada to the United States are not so frequent or cease almost altogether.

In summer, air is moving slowly into the continent in the northwest and rapidly out of the continent in the northeast. This causes a decrease in pressure over Canada. Warm moist air flows up across the United States from the south. This is shown in the left hand section of Figure 42.

It seems clear that when the Pacific is relatively warm at any season, and there are frequent movements of cold or cool air from Canada to the United States, the rainfall in the United States is increased. When the Pacific is relatively cold at any time of year, the overflow into the continent is reduced. In this case cold air masses moving from Canada are infrequent and rainfall is deficient.

These changes in pressure over the Pacific have another very important effect. In winter, when the Pacific is relatively warm,

pressure along the West Coast is low not only because of the air which flows more rapidly into the continent in the far north but also because there is a component of surface air movement from south to north over the ocean, making the air pressure lower in the Southwest. This low pressure in the Southwest causes moist Atlantic and Gulf surface air (arrow C in the left part of Figure 42) to flow far into the Great Plains and the Southern Rockies. On the other hand, in summer, when the Pacific is relatively cold, air accumulates off the Pacific Coast, and pressure rises in the Southwest until some air is forced over the mountains and some air is drained from the Mexican plateau. This air becomes dry and warm in descending and flows into the Great Plains replacing the moist air from the Atlantic and Gulf. These winds from the Southwest become the "hot winds of the plains."

To obtain a measure of this flow over the mountains and out of the plateau in the Southwest we can use barometer readings at a key point in the area and see the relation to the rainfall. Figure 43

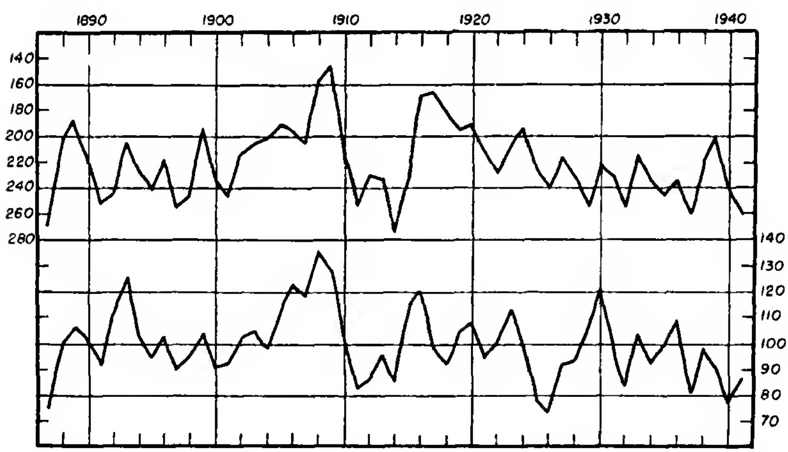


FIG. 43. Above. May barometer (station level) at Santa Fe, New Mexico. Inverted scale at left is in thousandths of an inch above 23.000 inches; for example, the mean barometer reading entered for May 1930 is the smoothed mean($\frac{a+b}{2} = b'$) for 1929 and 1930. Below. National rainfall in per cent of normal, smoothed same as upper curve. The observing station at Santa Fe was closed and there is no record after 1941.

shows (above) the average barometer readings at Santa Fe, New Mexico (elevation 7,013 feet), in the month of May each year from 1886 to 1941 and (below) the national rainfall each May in the same period. The barometer scale has been inverted because pressure and rainfall vary in the opposite sense; that is, high barometer means low rainfall and vice versa. Notice that

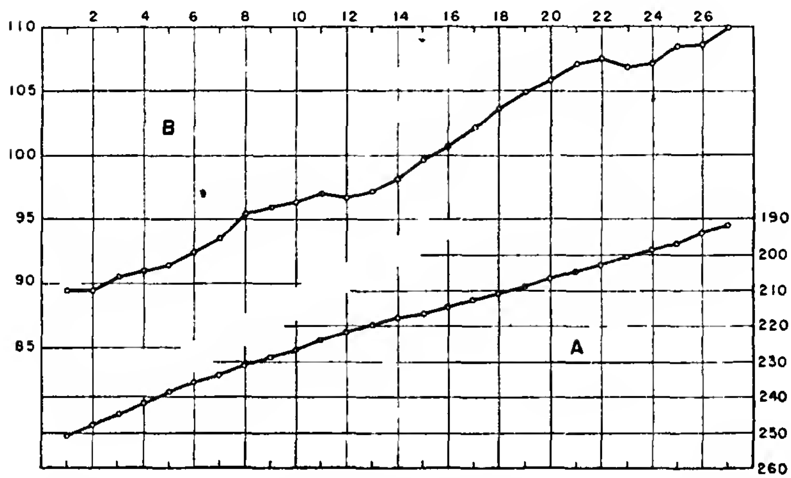


FIG. 44. This diagram shows at A 30-year means of May pressure at Santa Fe and at B national rainfall in May. The years were arranged in accordance with the height of the May barometer in the same manner as for annual readings in Figure 35 The pressure scale is 23 inches plus thousandths of an inch. Here we see that the slight pressure variation of about .060 inch is associated with a variation of about 20 per cent in national rainfall.

rises and falls in the May rainfall curve for the entire country agree in a large measure with the ups and downs of the barometer in May at Santa Fe. The ten high values of the barometer at Santa Fe correspond with average national rainfall 11% below normal; the ten low values correspond with national rainfall 11% above normal. Figure 44 shows 30-year means of pressure at Santa Fe and national rainfall in May.

In May the temperature is rising rapidly over the continent; the ocean temperature lags behind. Unusually low ocean tempera-

tures at this season produce a strong tendency for the air to come over the mountains and out of the plateau in the Southwest.

We now have another air current which must be added to those shown in the diagram in the left part of Figure 42. This gives us Figure 45, which includes the air coming from the mountains in the Southwest during periods of drought. It is believed that a part of this descending air, especially of that from the Mexican plateau, comes originally from the Atlantic anticyclone, moving in a broad arc southward and westward into Mexico and thence into the United States.

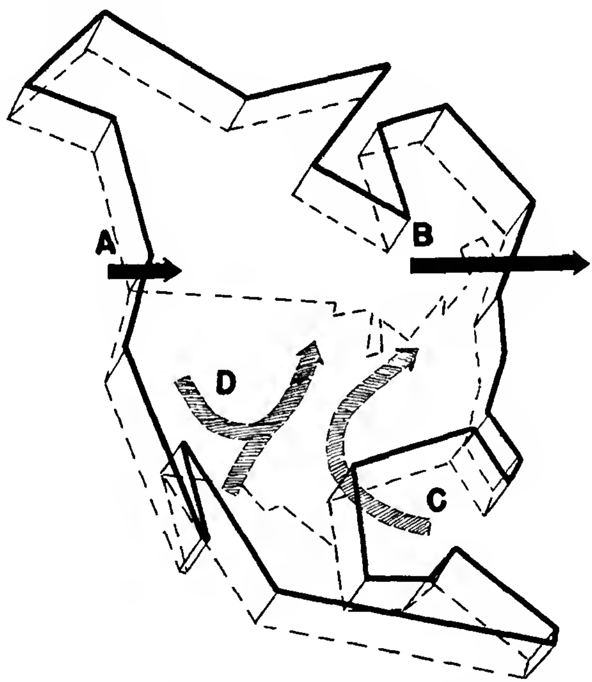


FIG. 45. In droughty weather, the continent is relatively warm and the oceans are relatively cool. Air current B is increased; A is decreased. The Atlantic and Gulf air C, which comes into the continent at the surface to make up for the inequality between components A and B, is turned to the eastward by air currents D which come over the mountains and out of the Mexican plateau. Little or no air comes from Canada to cause rain. Compare with Figure 42.

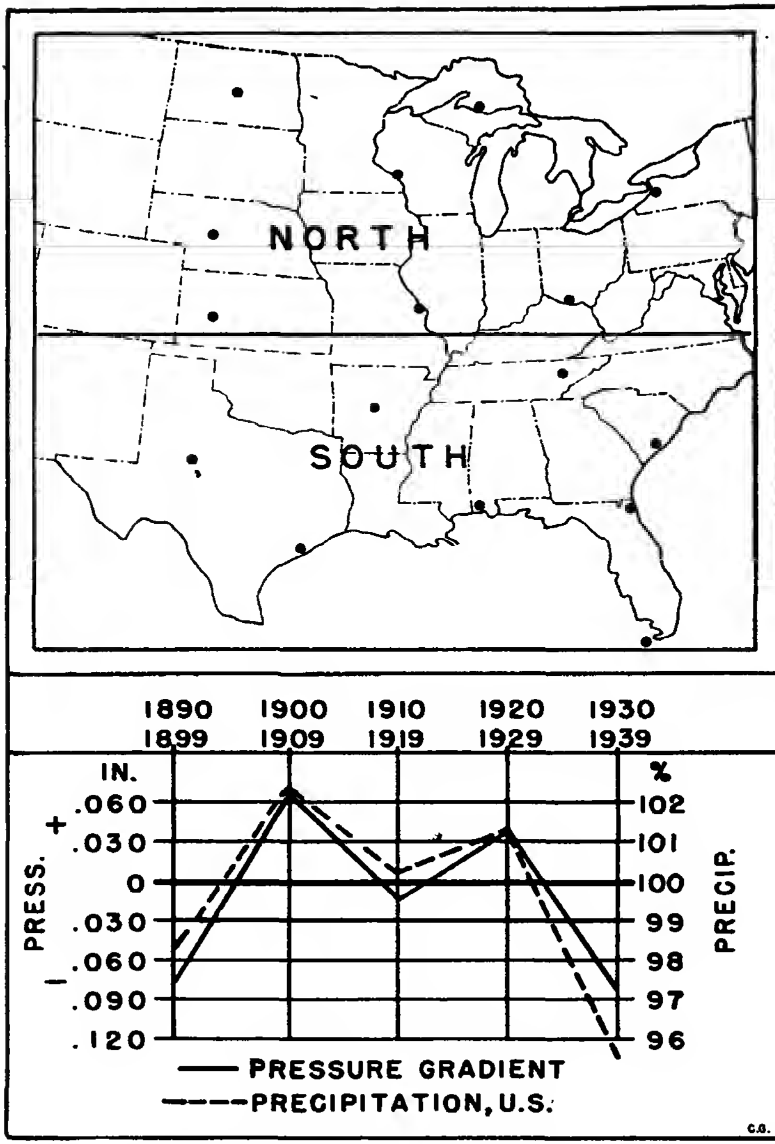


FIG. 46. For this diagram Kincer used eight points north and eight points south of the line across the middle of the map in the upper half of the diagram. He averaged the pressure departures and precipitation by decades. Differences of average pressure between points north and south of the line were used as the gradients. The values used for precipitation are weighted averages for the country as a whole. Notice that in the long run the years with relatively high pressures in the north are wet, and vice versa.

Of course, we cannot neglect altogether the effects of Atlantic and Gulf temperatures, but so far as control of national rainfall is concerned, it appears that they are secondary to the Pacific.

In 1941, Kincer,[21] who for many years studied rainfall variations in the United States, found that more rain falls when pressure is relatively high in the northern part of the country (Fig. 46), but he did not give any explanation. It seems evident that a relatively cold ocean will cause pressure to be high over the North Pacific and to be low over the northern United States. Low pressure in the northern United States is unfavorable for rain because (1) fewer cold air masses come from Canada to cause precipitation in the warm moist air, and (2) more frequent winds blow from the dry Southwest and divert moist air to the east and northeast.

In short, the desert in the Southwest is caused by the nearness of the *relatively* cold Pacific. When the temperature difference is especially great, the desert climate of our Southwest expands to the north and east. The mountain barrier is not a real barrier. The rain-causing winds come across in the north, and the drought-producing winds come from the mountains in the Southwest. The latter effect is especially strong in spring and early summer when the continent is becoming rapidly warmer and the Pacific remains relatively cool.

In this chapter May records were used to show what happens in the warmer season, with rapidly rising temperatures over the continent. We shall next look at what happens at the opposite season, in November, when temperatures are falling rapidly over the continent.

[21] Kincer, J. B., "Some Pressure-Precipitation Trend Relations." *Monthly Weather Review.* August 1941.

IX. NOVEMBER DROUGHTS AND THE G.B.A.[22]

THE Great Basin occupies a strategic position on our western weather frontier. It lies between the Wasatch Mountains and the Sierra Nevada. (Fig. 47.) Most of it is in Utah and Nevada but there is a large part in California. Smaller areas in Oregon, Idaho, and Wyoming are included. It is about 800 miles long, north to south, and roughly 500 miles broad in its widest part. The Great Basin is important in weather forecasting. There are times when cold dry air fills the Basin and it loses its heat rapidly by radiation, forming a sink. At such times air accumulates in this sink and a persistent "high" or anticyclone is likely to develop. This anticyclone is associated with the Pacific high when the latter is well developed. In other words, when pressure is high over the northern North Pacific it is usually high also in the Great Basin.

Cold air masses moving down from Canada through the Northern Plains, the Upper Mississippi Valley and the Great Lakes do not readily pass over into the Great Basin. These cold dense Canadian air masses lie near the ground, and the Rocky Mountains form an effective barrier. The air that crosses from the Pacific is dried out in passing over the mountains into the Great Basin. There is a definite connection between air pressure in the Great Basin (Salt Lake City) and the barometer readings at Portland. Pressure in the G.B.A. is high during periods when the Portland barometer is high, and vice versa. Pressure in the Great Basin varies with the season. The highest average is in November, but it is nearly as high in December and January. The highest November pressures are recorded in years when the Pacific high is well developed.

In November the G.B.A. is therefore related to rainfall in the United States. It feeds dry air into the Southwest. Sometimes, as

[22] Great Basin Anticyclone. An anticyclone is a "high"—a system of outflowing winds at the surface of the earth with high pressure at the center of the system.

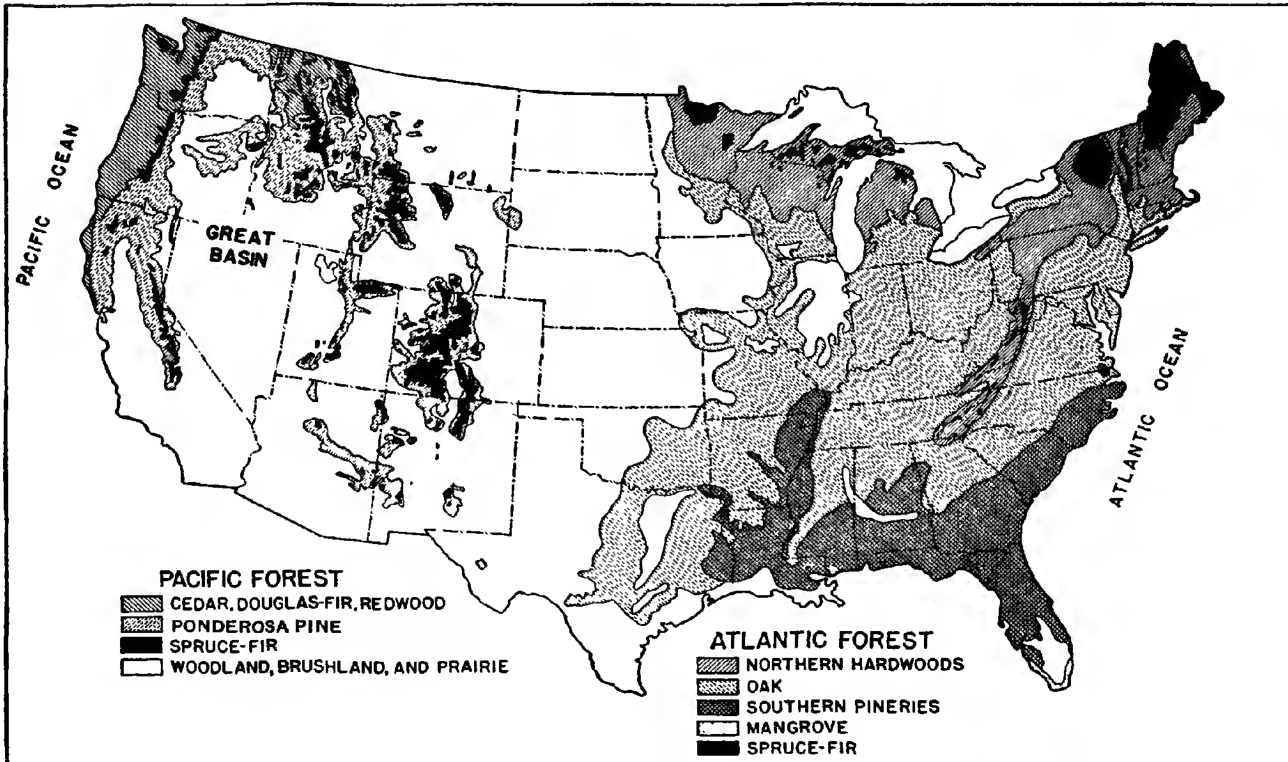


FIG. 47. The nation's forests. The Great Basin is outlined by forests on the slopes of surrounding mountains. (After Raphael Zon)

we have already seen, it causes Santa Ana winds in the vicinity of Los Angeles. To show the effect of the G.B.A. on rainfall, Figure 48 represents national rainfall in November (B) each year from 1886 to 1944 and average barometer readings (inverted scale) at Salt Lake City (A) in the same months. In the ten years when

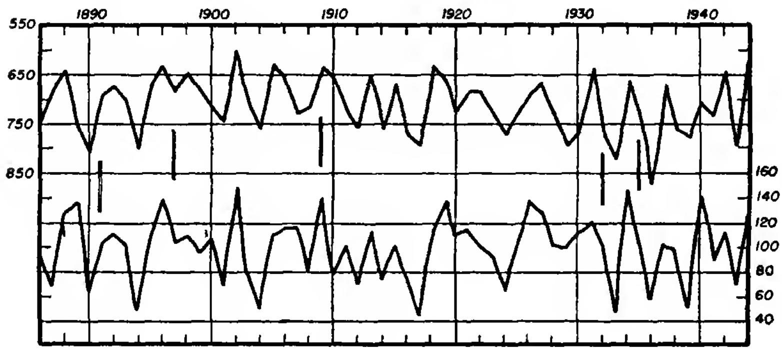


FIG. 48. Above. November barometer (station level) at Salt Lake City (representing the G.B.A.). Inverted scale at left is in thousandths of an inch to be added to 25.000, e.g., 650 is 25.650 inches. These are actual values, unsmoothed. Below. National November rainfall unsmoothed in percent of normal by scale at right. Short bars in middle of diagram indicate years when barometer was moved to a new location, but all readings are corrected to the elevation in 1900, which was 4,360 feet above sea level.

the November G.B.A. pressure (at Salt Lake City) was highest, the national rainfall averaged 37% below normal; in the ten years when pressure in November in the G.B.A. was lowest, the rainfall averaged 20% above normal in the United States. Figure 49 shows 30-year means of Salt Lake City pressures and national rainfall in November.

The G.B.A. is nearly as well developed in December and January as in November. Figure 50 illustrates this. In January 1916, the national rainfall was the greatest (170%) of any January from 1886 to 1944. In January 1928 it was the least (53%) for the same years. The two charts show the G.B.A. in these two months. In 1928 the G.B.A. was well developed and high pressure dominated the Southwest. In 1916 the high pressure area was in the Northern

Plains and low pressure covered the Southwest. In January 1928 the average pressure at Salt Lake City was 25.822; and in January 1916, it was 25.474. These were the highest and lowest respectively, for the years from 1886 to 1944.

The simple relations shown here and in preceding chapters between pressures at points in the west (Portland, Santa Fe, and Salt Lake City) and the national rainfall bring up three questions:

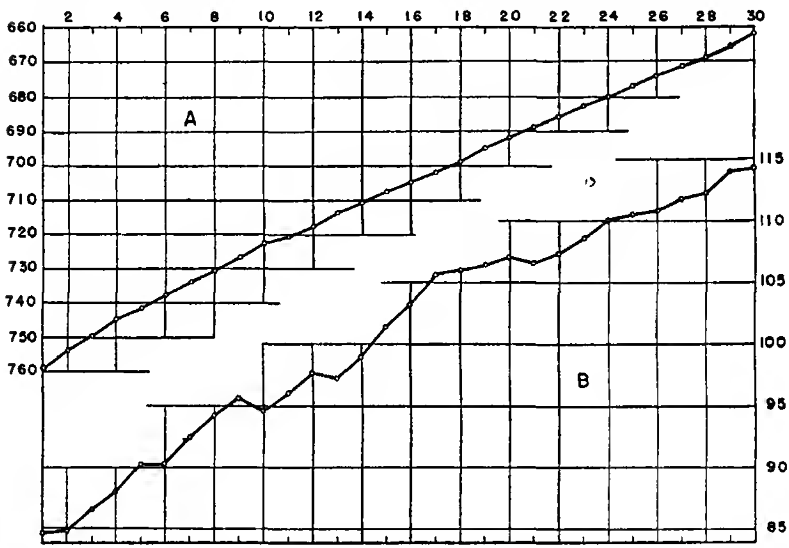


FIG. 49. The diagram shows at A the 30-year means of November pressure at Salt Lake City and at B national rainfall in November. The years were arranged in accordance with the height of the Salt Lake City barometer in November in the same manner as was done in Figures 35 and 44. The pressure scale is 25 inches plus thousandths of an inch. Here we see a pressure variation of .098 inch associated with a variation of about 30 per cent in national rainfall.

First, to what extent does the variation in rainfall in the western states determine the national average? In other words, is this variation of national rainfall a reflection of the rainfall in the Far West rather than for the whole country? As a partial answer to this question, the record shows that in the ten Novembers (1886-1930) with highest pressure at Salt Lake City, the average rainfall

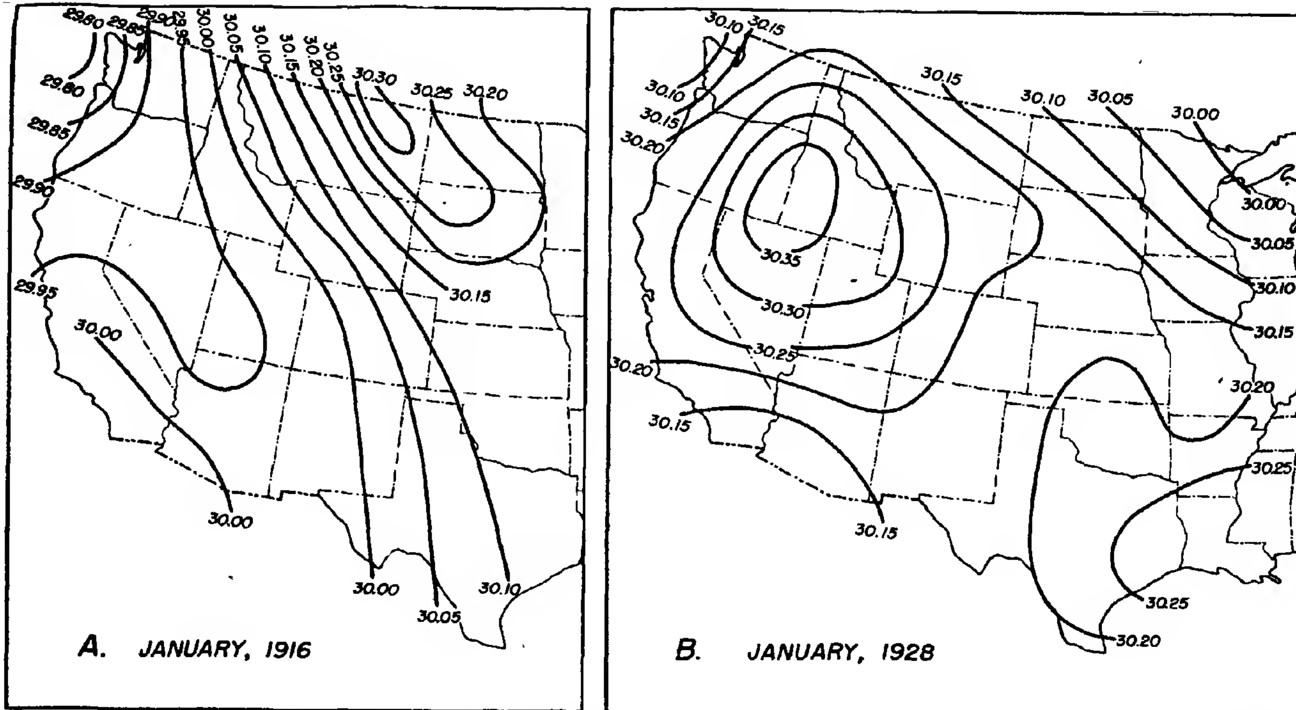


FIG. 50. Distribution of monthly means of pressure reduced to sea level in (A) January 1916, when rainfall for the nation averaged 170% of normal, the wettest January in the records, and (B) in January 1928, when the national rainfall averaged 53% of normal, the driest January in the records. In 1916 high pressure covered the northern plains and the G.B.A. was absent. In 1928 the G.B.A. was strongly developed.

at St. Louis was 1.49 inches; in the ten Novembers with lowest pressure at Salt Lake City, St. Louis had an average of 3.02 inches, or more than twice as much.

The second question bears on the first: If droughts are as irregular and difficult to understand as was stated in Chapter III, how does it happen that there is such a simple relation (Figs. 48 and 49) of Salt Lake City pressure to national rainfall? The answer: Pressure at Salt Lake City (or Portland, or Santa Fe) is merely a good indication of the broad relation between air temperatures over the continent and the oceans. This is a broad control of the amount and distribution of rainfall over the United States as a whole. There are many irregularities which are smoothed out in the national averages. Salt Lake City pressures may not always be a good indication of November rainfall at any one place such as San Antonio, Texas, or Bismarck, North Dakota, or Richmond, Virginia. It may be a good indication of the average for a period of years, as in the St. Louis example just given. These local irregularities are smoothed out in the national averages and there is a definite relation between the G.B.A. and the national rainfall.

Third, if cold air masses from Canada are so important in producing rain, and these air masses are much more prevalent in late autumn and winter (when the Pacific is relatively warm) than in late spring and summer (when the Pacific is relatively cool), why do we not have much more rain east of the Rockies in the colder part of the year than in late spring and summer? The answer: In the cold season these cold air masses are often so strong that they dominate the weather of the continent east of the Rockies. Nearly all of the air movement is outward from the continent to the oceans. Little or no warm moist air can come into the country, and during these intervals we have dry, clear, cold weather with little or no rain or snow. In the intervals of winter when the outbreaks of cold air from Canada are not so strong, there is much rain or snow, as we would expect.

The facts which have been presented in the preceding pages are intended to show that the dominating influence in broad-scale drought development is the Pacific Ocean, a fact which has not been recognized before. A large proportion of the moisture which

makes rainfall in the United States, especially in the territory east of the Rockies, is carried inland by winds from the Atlantic and Gulf. The rate and direction of movement of these winds are modified to some extent by the temperature contrasts between the Atlantic and Gulf on the one hand and the continent on the other. Later we shall see some of these effects. The evidence, however, points to primary control by the Pacific Ocean.

In 1928, A. J. Henry, who was for many years a diligent investigator of the causes of rainfall variations in the United States, included the following statements in his conclusion with regard to the anticyclone in the Great Basin:

"It can be laid down with much confidence that months with more than normal precipitation in California are those in which pressure in the Gulf of Alaska is considerably below the average. In other words, the low-pressure center normally found over or near to the Aleutian group of islands is displaced to the southeast, the G.B.A. cannot form, and southerly winds with abundant rains prevail in California." But he continued: "We deceive ourselves when we create the impression that a study of the current and accumulated data of the Pacific will point the way to seasonal forecasting for the North American Continent; nevertheless we should not on that account refrain from a sustained effort to summarize and place in convenient form for statistical analysis the current and accumulated meteorological data for the Pacific Ocean."

These statements indicate that Henry entertained a suspicion that the Pacific pressure situation is the key to broad rainfall control in the entire United States as well as in California, but he hesitated to accept what seemed to be a preposterous idea that the Pacific might control rainfall east of the mountains. Henry had to contend with the added difficulty that the irregularities in rainfall are quite confusing, as are the occurrences of drought, and unless the problem is considered on a national basis in simple terms, the broad controlling influence of the Pacific fails to appear clearly, and the natural tendency is to deny that there is any relation.

In a study of summer hot winds on the Great Plains, I. M. Cline

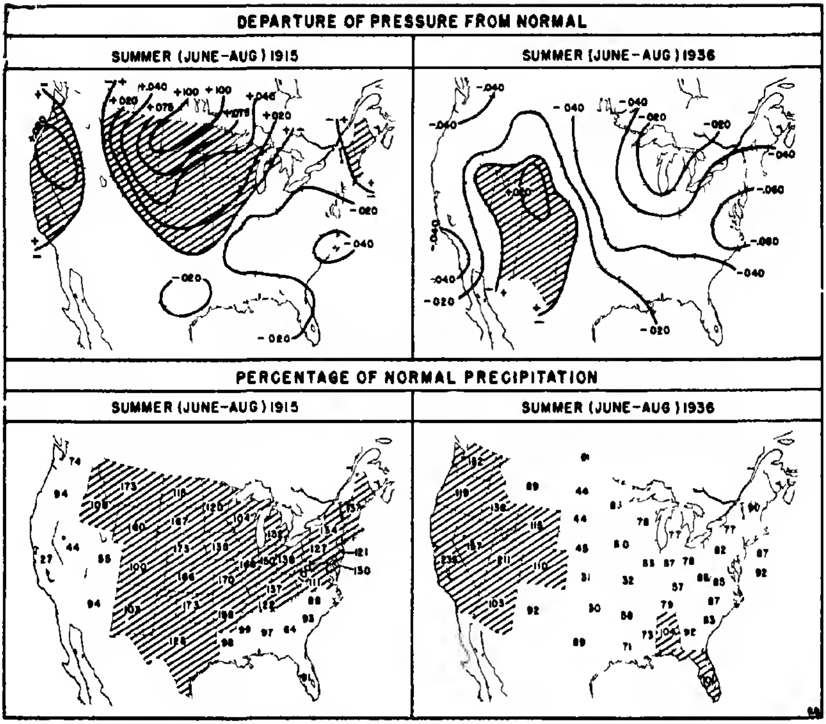


Fig 51 Above left High pressure reaches into the northern plains Above right High pressure reaches into the southern Great Plains Precipitation results are shown below (Kincer)

found (1894) that in nearly all instances the winds came from the plateau region and descended the eastern slope of the Rockies to the Great Plains. He said, "Apparently the conditions on which the development of hot, dry winds over the eastern slope of the Rocky Mountains and eastward depends are the presence of nearly stationary or slow moving low pressure areas along the eastern slope and then eastward, with a relatively high pressure over the Pacific off the coast of Oregon or in that vicinity." Cline concluded, however, that "the development of these hot winds is entirely independent of drought conditions."

One fact seems to be clear. There is a seasonal change in the Pacific high because of the seasonal change in the ocean-continent temperature contrast. Therefore, as the Pacific high changes its

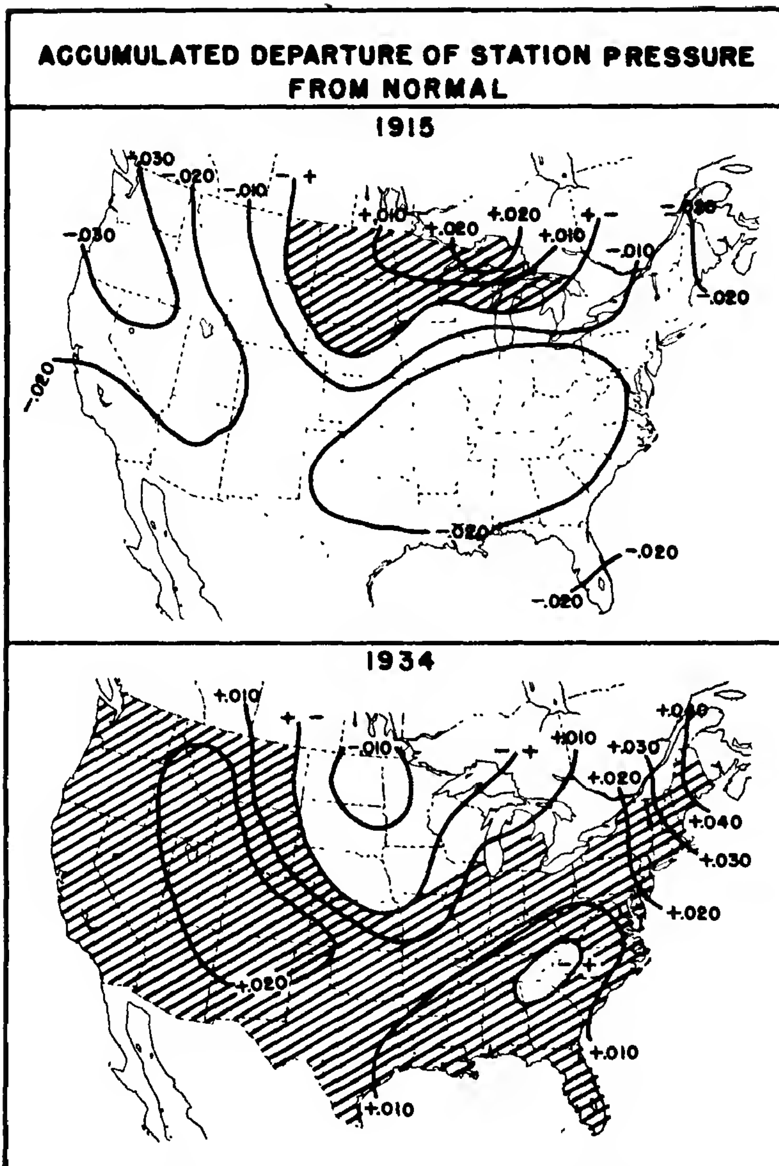


Fig. 52. Departure of pressure from normal in the wet year 1915 and in the great drought year 1934. Shaded portions show pressure normal or above. (Kincer)

size and position from month to month, it is necessary to change the place where the pressure is measured so as to get the best indication; for example, Santa Fe in May (Fig. 44) and Salt Lake City in November. (Fig. 48.)

We have come to one definite conclusion: There are other influences which heighten the drought in local areas and make it less serious in others, but the general pattern of drought in the United States is under Pacific control and, because of the mountain barrier, the control is exercised through the upper air. It is interesting to note at this point the departures of pressure from normal in the wet year (1915) and the great drought year (1934) as shown in Figure 51.[23]

[23] These changes in air movement across the mountains to the north or south represent components of the general circulation of the atmosphere. Measurements at higher levels in the free atmosphere are not sufficiently precise and have not been made for a period of time long enough to show these variations in detail above the earth's surface. In general, during a given month in one year when the northern branch predominates and rainfall in the United States is abundant, the upper air soundings in the Pacific States show pressure in the upper air to be relatively low to the northward. When in the same month of another year the southern branch predominates and rainfall in the United States is deficient, pressure as shown by upper air observations in Pacific States is relatively high to the northward.

X. WHAT ABOUT THE GREAT PLAINS?

EVERY farmer wants to know how much rain will fall on his acres and when. Of course he is interested in rain that will fall on neighboring farms and in adjoining counties, but it does no good to his crops unless he gets his share. If he can't know exactly how much he will get, he wants to know something about his chances. That question is of supreme importance in the vast area between the Mississippi River and the Rocky Mountains, and it is paramount in the Great Plains.

We talk of rainfall over the nation as a whole. What does that mean so far as the Great Plains are concerned? (Fig. 53.) The answer to that question is encouraging. In general, we can give the same kind of answer that politicians formerly gave in predicting the outcome of national elections, "As Maine goes, so goes the nation." And we can confidently say in regard to rainfall, "As the Nation goes, so go the Great Plains."

Figure 54 shows some data analyzed by Kincer.[24] We see by inspection that of the three great divisions of the country, none reflects the national trends as well as the great middle region from the Mississippi to the Rockies.

If we use the records of individual places as an indication of rainfall in any region we get into trouble. There are all sorts of local variations. A single thunderstorm could hover over a rain gage in a semi-arid region and produce a rain measurement that would take years to smooth out in the averages. It is not reasonable to conclude that we can use the catch of a single rain gage in this vast trans-Mississippi territory to indicate the variations of rainfall for the entire region. But in the long run the great Pacific Ocean in its reaction to the changes in the relative position and heat of the sun is the deciding factor. There is no place in the

[24] Kincer, J. B., "Climate and Weather Data in the United States." *Climate and Man*. Washington, 1941.

trans-Mississippi region where the farmer can get away from that powerful influence.

For example we can use the rainfall records at North Platte in western Nebraska. The soil in this area is remarkably fertile, but it is located far from the sources of moisture, in the shadow of the Rockies, subject to the cold dry outpourings of Canadian winters and the hot winds of the Great Plains in season.

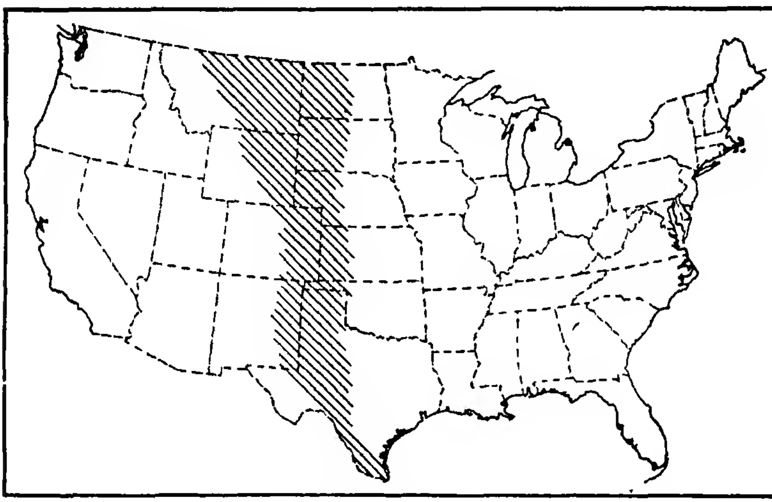


FIG. 53 Hatched area shows the Great Plains (From *Climate and Man*)

We take the national rainfall percentages in groups. First, there were (1886 to 1943) 12 years which we shall call Class A, when the nation's rainfall averaged more than 105% of normal. In those 12 years the rain gage at North Platte caught an average of 23.10 inches. There were 31 years (Class B) when the national rainfall was near normal—not more than 105% or less than 95% of normal. North Platte in those years averaged 17.53 inches. There were 15 years (Class C) when the national rainfall was less than 95% of normal. In those years North Platte averaged 14.13 inches.

In the Class A years the barometer at Portland averaged 29.876;

in Class B, 29.893; in Class C, 29.905. These data are shown in the table:

Class	National Rainfall	North Platte Rainfall	Portland Barometer
A	More than 105%	23.10	29.876
B	From 95 to 105%	17.53	29.893
C	Less than 95%	14.13	29.905

In the minds of those who study daily weather maps and see the large changes of pressure commonly appearing (sometimes of the order of an inch or more in a day), it seems almost foolish to assume that small pressure differences, in thousandths of an inch, could be related to national changes in rainfall of such great importance. On the other hand, in the 15 dry years when the pressure at Portland averaged 29.905, only 12 thousandths of an inch above normal, it must be noted that during these years this small average pressure difference was maintained with the atmosphere constantly striving to find an equilibrium, that very great movements of the atmosphere were involved in the aggregate, that some powerful force had to be applied to maintain even this small difference, and that Portland pressures are an index to what may be larger pressure changes over the ocean or in the relative distribution of pressure over ocean and continent.

Of course, there are important seasonal differences in rainfall between the northern and southern parts of the Great Plains. Some of the facts in the pages that follow will have a bearing on such variations in rainfall distribution. In any event, if we maintain accurate records and do not move our instruments from place to place, we shall eventually have what we need for a detailed study and understanding of the more important of these regional variations. Readings must be accurate and strictly comparable. These extremely small yet highly significant pressure differences are likely to be lost when barometers are moved from city offices to airports or when their elevations are changed for other reasons. In this study of drought we have used the readings actually taken from the barometers without reduction to sea level. On daily weather maps we necessarily use readings corrected to a common

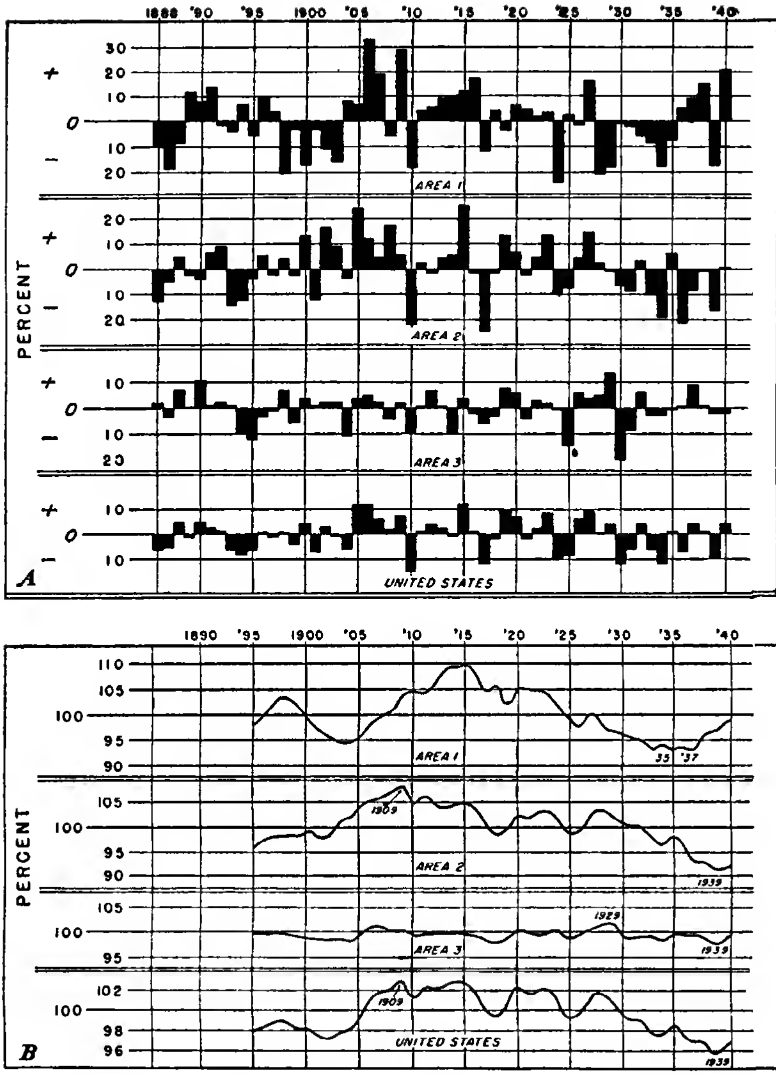


FIG. 54. Above (A). Year-to-year unsmoothed precipitation in percent above or below normal. Area 1 is the western part of the country to the Rockies, area 2 is from the Rockies to the Mississippi; area 3 is from the Mississippi to the Atlantic. These values are based on state averages weighted according to state areas. Below (B). Each point on these curves is a 10-year average in per cent of normal, up to and including the date where the point is plotted, e g , for the United States 98 per cent in 1895 is the average from 1886 to 1895, inclusive. (Kincer) Data for these graphs will be found in the Appendix.

level. The surface weather map is built around pressures reduced to sea level by adding in each case the weight of an imaginary column of air between the barometer and sea level. In the mountainous region of the West and at higher elevations generally, this practice leads to inaccuracies which are negligible in mapping the daily weather but which obscure important pressure changes which endure in longer periods of time, as in the case of drought.

Sometimes it is obvious that the removal of the barometer locally from one building to another or from city to airport has affected the corrections so that there is a slight discontinuity in the records. In Figures 39 and 48, changes in elevation of the barometer are indicated. The Weather Bureau continues to be careful to correct these readings to one fixed elevation in the vicinity, but even some of the small inaccuracies in these slight corrections appear in the longer-term relations between pressure and rainfall The rainfall records used in this book are chiefly state and national averages and hence are not affected much by changes in exposures of the individual rain gages.

In the long-period trends of rainfall as measured for the year as a whole, there is a great deal of similarity in the variations in different parts of the plains region. Figure 55, prepared by Kincer, shows that the main features of the trends of yearly rainfall in the Dakotas and Minnesota have been similar to the trends for the combined records of Las Animas, Colorado, and Dodge City, Kansas.

The Great Plains, lying just east of the Rocky Mountains, are more strongly under Pacific control than any part of the United States except the area between the mountains and the Coast. The Dakotas and that part of Montana which is east of the mountains form a broad channel through which cold or cool air masses enter this country from Canada. During the winter, and at other times when these dry northerly winds blow across this area and moist winds are blocked farther southward, the northern part of the Great Plains may be dry while the southern Great Plains may get some rain. But the hot winds of summer and warm dry winds at other seasons enter the Great Plains from the Southwest. and that region may be dry while moist winds, especially in June or

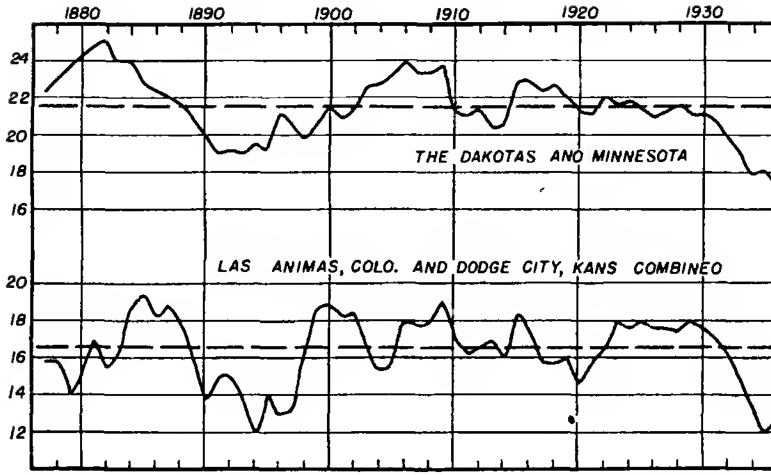


FIG. 55. Annual precipitation for ten years ending at dates plotted, showing similarity in trends in (1) Dakotas and Minnesota and (2) Las Animas and Dodge City. (After Kincer)

July, may reach far to the northwest and bring some rain in the Dakotas and eastern Montana. This is the mechanism which gives us a strongly seasonal oscillation in rainfall between the northern and southern parts of the plains region.

Figure 56 shows 5-year means of annual rainfall for North Platte (A) and the United States as a whole (B). The similarities in the variations are apparent. But these are annual amounts. The pattern of rainfall and barometer readings varies with the seasons. Averages for the year eliminate many features which are characteristic of the response of the atmosphere to the march of the sun through the heavens and to the stubborn efforts of the oceans to resist the changes decreed by variations in the sun and the relative position of the earth in its orbit.

In the Western Range as a whole there are numerous local peculiarities in rainfall distribution. Mountains and valleys produce innumerable local complications which are not even suggested by a small scale map of the type shown in Figure 57. Each one of these local situations should be treated separately.

One billion acres in the United States are used for grazing during at least a part of the year. This represents nearly 60 per cent

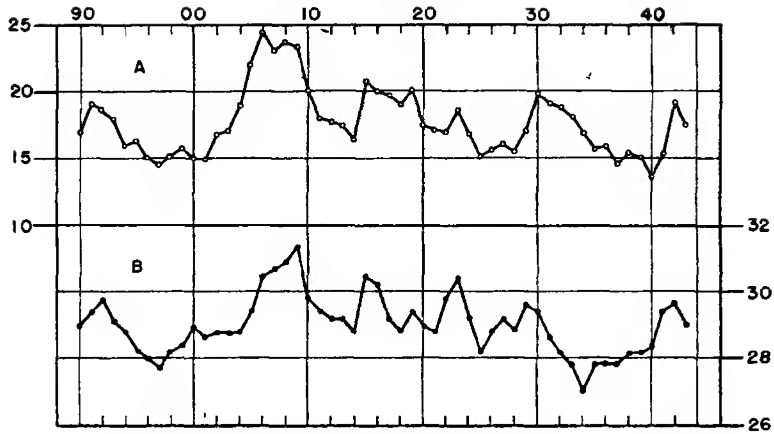


FIG. 56. Five-year means of yearly rainfall (A) at North Platte, Nebraska, and (B) for the United States. Scales show rainfall in whole inches. Values for 1890, for example, are means for years 1886 to 1890, etc.

of our total land area. Much of this grazing land receives less than 20 inches of rain annually and a considerable part of it less than 10 inches. Our grazing lands support about 70 million cattle and more than 50 million sheep. In the dry range country of the West, the situation regarding rainfall is always precarious. While we worry about an occasional drought in the more populous farming areas of the country, much of the range country subsists and even prospers on what amounts to a never-ending drought by our eastern definitions. In winter, livestock are kept in feed lots and on winter ranges, a large share in the lower valleys and on the edges of the desert in the Southwest. In spring they begin the trek toward new growth on spring ranges. Hundreds of thousands of sheep are involved in these migrations. Some flocks travel more than 200 miles. In the range country rain means everything. Man obeys the dictates of climate and has no more trouble in the long run than his brother on lush pastures farther east.

In the preceding chapters we have looked at the records to find the primary cause of rainfall variations. Next we shall consider in more detail the processes involved in seasonal variations and longer-term changes.

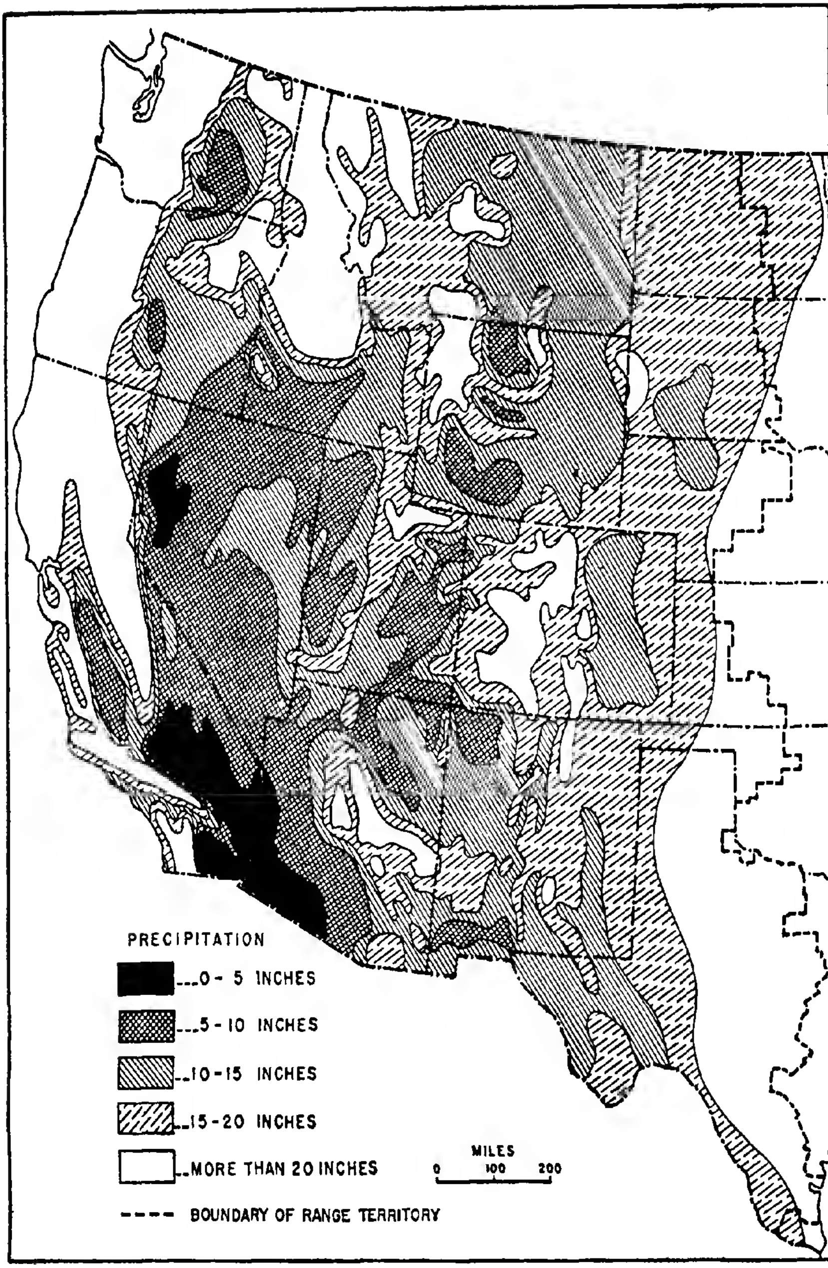


FIG. 57. Main rainfall zones in western range territory. (From *The Western Range*)

XI. HOT SUN AND COOL WATER

NEARNESS to water does not assure rainfall. In the midst of vast stretches of ocean there are islands, such as St. Helena, Ascension, and the Galapagos Islands, whose shores have the climate of deserts. Cool ocean currents are responsible for this condition. Constant movements from cooler to warmer latitudes bring these waters under the direct rays of the sun. The water is not cold; it is relatively cool, compared to the land.

Key West is surrounded by water. The warm Gulf Stream is practically in the front yard. Almost every year in late winter or early spring there is a drought at Key West, with winds blowing off the water. Lack of rainfall there is of no great concern, but the facts are interesting. At this time of year the sun is coming northward. The air is getting warmer and the water is relatively cool. The driest month from January to April at Key West in each of the sixty-one years from 1870 to 1930 averaged only 0.41 inch. In some years one of these months at Key West had too little rain to measure (less than 0.01 inch). At the other extreme, late summer and early autumn at Key West are wet. The wettest of the months from July to October in each of the same sixty-one years averaged 9.03 inches. Six of these months had more than 15 inches each. At this time of year western Atlantic waters are relatively warm and the sun is going south.

In the succeeding chapters, in order to avoid confusion when speaking of the condition of the sun, we shall use the following convention. When we mean that the actual radiation from the sun is changing, we shall refer to a *hot* sun and a *cool* sun, or a *hotter* sun and a *cooler* sun. As the earth on its tilted axis travels around the sun, we have the changes of the seasons. In summer, when the Northern Hemisphere is tilted toward the sun, the sun's rays strike the United States more directly, and the sun *feels hotter.* The path of the sun across the sky is high, and at noon it passes almost directly overhead. To describe this condition (when the sun merely *feels hot*), we shall say that the sun is *high.* In

winter, when the Northern Hemisphere is tilted away from the sun, the sun's rays strike the United States at a glancing angle, and the sun *feels cool.* The sun travels a low path across the sky, never going so far from the horizon as it does in summer. To describe this condition, we shall say that the sun is *low.*

In the spring the effect of cool Atlantic waters and a high sun is sometimes felt far into the interior of the continent. Local or temporary droughts occur. They are temporary because the cool water is mostly along the eastern shores with the warm Gulf Stream outside, or along the northern coast of the Gulf of Mexico These coastal waters become warmer as the season advances, and rain comes again. If the Pacific is relatively colder than usual, these local and temporary Atlantic and Gulf drought conditions are added to the more widespread Pacific effect and the drought may be serious.

On the Pacific side the water does not become warm enough in summer to permit rain along the coast. The cool waters there are part of a cool ocean current, which persists through the warm season. The drought hangs on all summer in Pacific coastal areas.

On the other hand, local and temporary droughts are caused also by dry winds blowing outward from the interior of the continent. Relatively warm Atlantic and Gulf waters aid this outdraft. The Northern Plains afford a good example. In winter, cold dry winds from Canada prevail in North Dakota. On the southern borders of these cold air masses there may be much rain where moist winds are forced up over the cold air, but in North Dakota the cold dry winds of winter nearly always are established beyond the reach of moist air. Bismarck, for example, averages only about 0.50 inch in January and February, and has only slightly more in December.

One might ask why these cold winds from Canada are dry. Cold air masses are dry only because the moisture has been taken out of them. What has become of the moisture? In this case the answer is obvious. The mountain rain wringer to the westward is almost constantly busy in winter taking the moisture out of the air from the Pacific before it settles down into the Canadian sink. These mountain slopes facing the Pacific are in the wettest region

in North America. Here we find the rain and snow that the Northern Great Plains often fail to get in the winter time. The air that reaches Canada from the Pacific must go over the mountains. In going up it becomes cold and loses its moisture, and in coming down its temperature rises somewhat and it becomes dry. The air at the upper level is so very cold that in spite of the rise in temperature on descending, it reaches Canada still very cold.

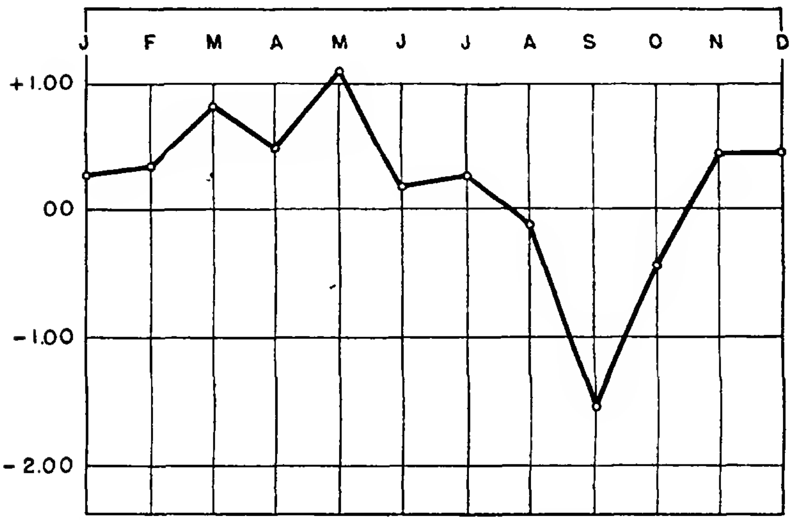


FIG. 58. Differences of rainfall between Galveston and Houston, Texas, by months. Scale at left shows excess or deficiency of Houston rainfall in inches as compared with Galveston.

Also, while over Canada, this air loses heat rapidly by radiation under clear skies.

Droughts due to outflowing continental winds usually are temporary, except in the Northern Plains. But these occur mostly in winter when precipitation is not important except as a reserve for the coming season.

The preceding facts bring us to the conclusion that high sun and cool waters make droughts on the borders of the continent, and low sun and warm waters make droughts in the interior of the continent.

Drought often seems complicated, but it is primarily a question of sun and water. For example, consider the rainfall at two Texas cities, Galveston, at the edge of the Gulf of Mexico, and Houston a short distance in the interior, only about 50 miles apart. (Fig. 58.) When the sun is high and the water relatively cool, Houston in the interior gets more rain than Galveston on the coast. When the sun is low and the water relatively warm, Galveston gets more rainfall than Houston. The differences between May and September average about 2.5 inches. In May Galveston gets about an inch less than Houston and in September nearly an inch and a half more than Houston. The rainfall records for Boston and Waltham, only ten miles apart, show the same effect. The difference in rainfall during the course of the year averages about three-fourths of an inch even in this short distance.

We have seen how the Pacific, with its high pressure area off the west coast, controls the flow of air over the mountains into North America. The Atlantic also has a high pressure system. Like the one in the Pacific, it lies in the eastern part of the ocean. Its

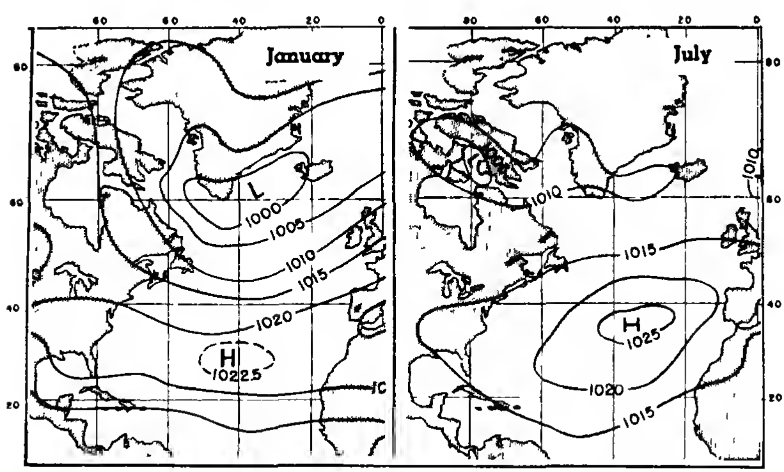


FIG. 59. The Atlantic high in January and July (pressure in millibars). In January the high (H) is small and located to the southward with a deep low (L) near Iceland and southern Greenland. In July the high (H) is expanded and located farther to the northward. The low near Iceland and southern Greenland is poorly developed.

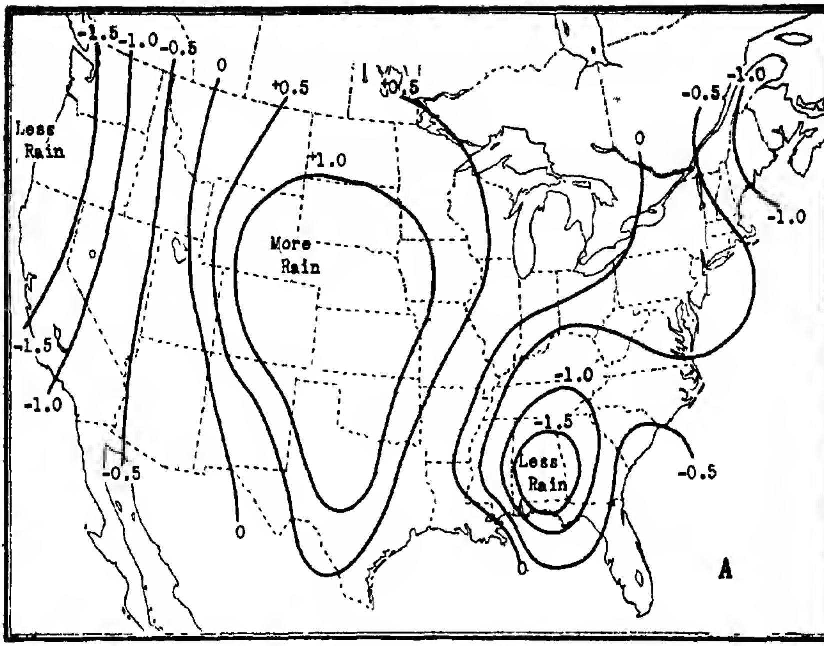
center is usually near the Azores. (Fig. 59.) At times there is a westward extension of this high in the neighborhood of Bermuda. This extension is known as the "Bermuda High."

It is commonly said that the "Bermuda High" brings hot, humid weather in the eastern part of the United States. This is incorrect if it is intended to imply that hot air comes from Bermuda. But the high pressure over the Atlantic and its westward extension do play an important part in the flow of moist surface air across the United States east of the Rockies. This air usually comes inland in the South Atlantic and Gulf States. It travels around the Atlantic high, gathers much moisture from the ocean, and becomes warmer in summer as it comes into the southern or southeastern part of the United States. In winter this air feels very warm as it comes into northern latitudes where colder winds are felt most of the time. In summer, the temperature and humidity of these air masses are high.

Like the Pacific high, this high pressure over the Atlantic moves southward when the ocean is relatively warm and extends to the northward and westward when the ocean is relatively cold. The moist surface air current which flows around the high therefore shifts to the north or south in accordance with the position of the high. This is one of the causes of the swinging-back-and-forth of the rainfall in the United States. Thus we see that while the Pacific largely controls the *amount* of rain which is precipitated over the United States, the Atlantic controls to some degree the *distribution* of the rainfall. At times there is more rainfall in northern states and less in the south and at other times there is more in the south and less in the north. This is illustrated in Figures 61 and 73.

The long-term rain-distribution influences of the Atlantic and Gulf on the one hand, and the Pacific on the other hand, cannot be separated clearly. It is obvious that when the sun gets higher and the continent becomes warmer, *both* the Pacific and Atlantic will tend to be relatively cool. If there are variations in solar radiation, an increase in the sun's heat in the spring months will make the temperature contrast with *both* oceans greater still.

Figure 73 shows the difference in rainfall between Chicago and


-1.5
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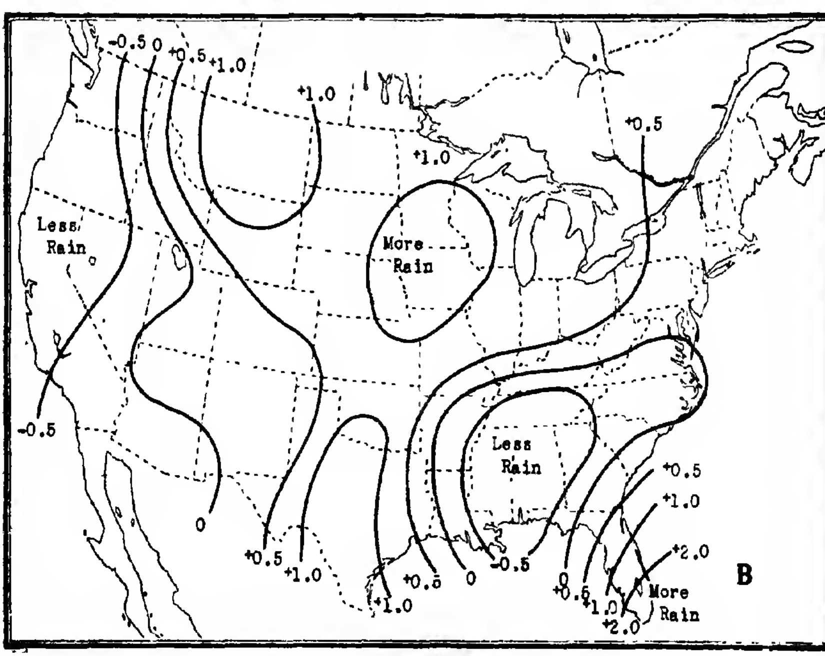
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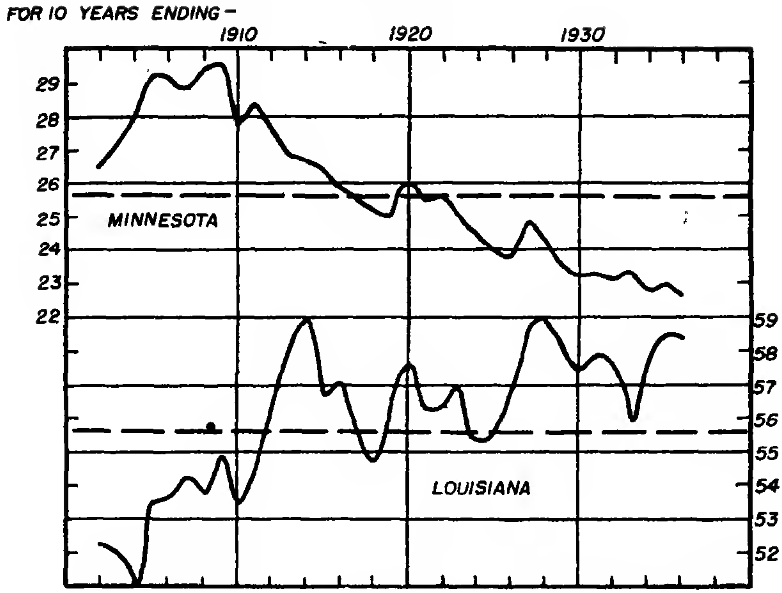


FIG. 61. Precipitation for ten years ending at dates plotted, for Minnesota and Louisiana showing opposing trends. (After Kincer)

Galveston in April for more than fifty years. The important fact to be noted in this diagram (Curve B) is the very large swing between north and south with an average amplitude of about two inches, which is more than two-thirds of the April average at Chicago and more than half the average at Galveston.

These curves show an important oscillation back and forth between northern and southern sections. The same force which produces more rain at Houston than Galveston in the spring of the year must also cause more rain at Chicago than at Galveston in certain years when solar radiation and ocean temperatures are favorable. This north-south oscillation in rainfall is also illustrated in Figure 86.

Figure 60 shows the effects on rainfall distribution of increasing continental temperatures in the spring months when the ocean temperatures lag. The upper chart (A) shows differences of rainfall between March and April and the lower chart (B) differences between April and May (50-year averages for selected places).

Positive values and the entry "More Rain" show excess in April over March and in May over April; negative values and "Less Rain" show the reverse. Here we see the Pacific becoming relatively cooler and the rain deficiency and summer drought developing in the Far West, while the increasing coolness (relatively) of the Atlantic produces an area of rain deficiency in the east and southeast.

In Chart B of Figure 60, there is increasing rainfall locally in Florida and the relative deficiency continues in the middle Gulf States, but in both charts rainfall increases in the Middle West, although Chart B shows a tendency for the rain to be carried farther northward in the interior. (See Fig. 70.)

Figure 61 by Kincer[25] shows the opposing trends of rainfall in Louisiana and Minnesota. Figure 62 shows trends in the plains region. The variations in the plains are similar. North Dakota, for example, shows a slight downward trend while the Oklahoma trend is upward, but there are some wide variations.

The reasons for these differences in trends between northern and southern states will be given in later chapters. Here it is only necessary to establish the fact that important swings in rainfall distribution exist.

Before we can go further with seasonal changes in rainfall distribution it will be necessary to consider the movements of the air and its cargo of water vapor. Much of the moisture in the atmosphere is invisible. We measure the amount of moisture in the surface air by instruments, and we obtain some measurements of moisture in the upper air by sending up balloons with instruments which send radio signals back to earth to register the temperature, pressure, humidity, and winds. We also judge the humidity by observing fog, and especially the various kinds of clouds and their heights above the earth. Our knowledge of the moisture in the atmosphere is always sketchy. As we have seen, there are places in the tropical oceans where it rains very little and the skies are clear nearly all of the time, and yet a great amount of moisture may be present in the atmosphere. We cannot rely on cloudiness as an indicator of moisture in the atmosphere. We shall consider some of these questions in the next chapter.

[25] Kincer, J. B., *Is the Climate Changing?* Springfield, Illinois, 1937.

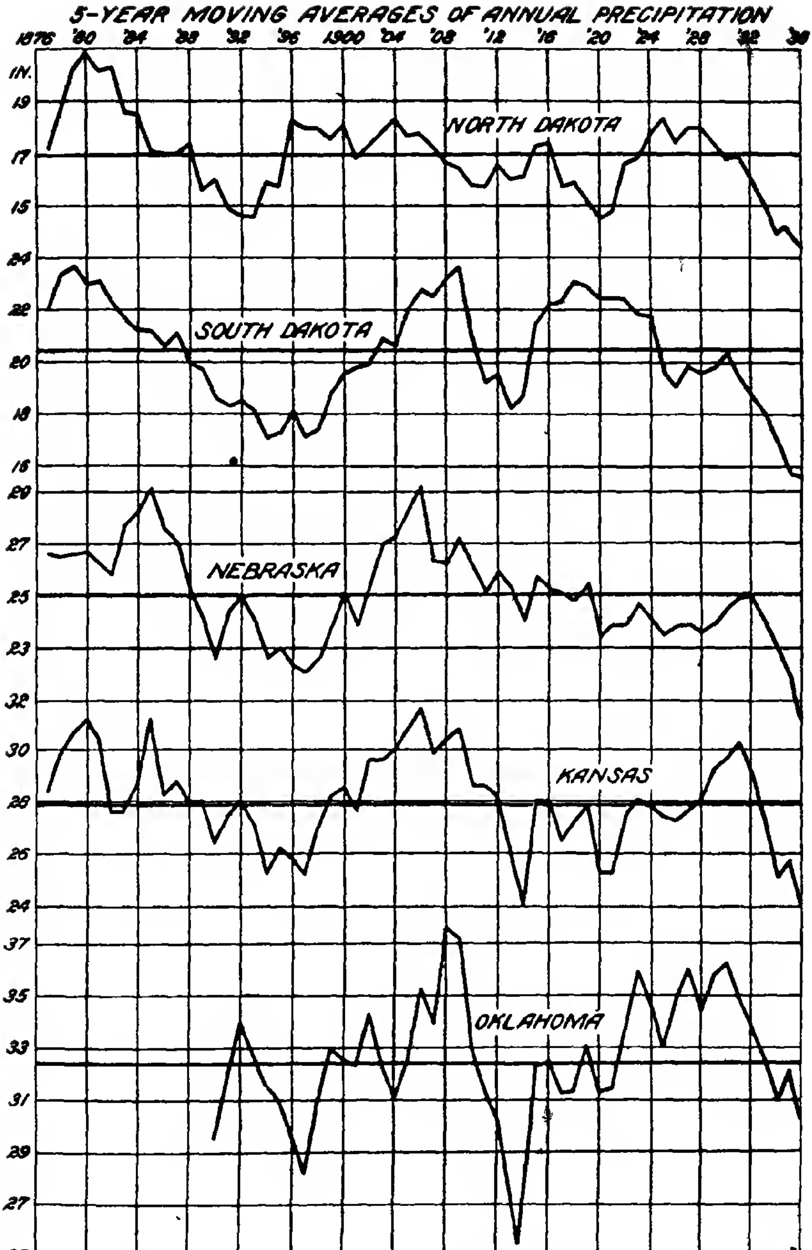


FIG. 62. Precipitation trends in the Plains Region. (After Kincer)

XII. THE ATMOSPHERE AND ITS MOISTURE

WE have made only a small beginning in the job of gathering the data needed to understand all that goes on in our atmosphere. This atmosphere is everything to us. We are born, we live, and we die in the thin skin of air that surrounds the earth. We breathe it; it brings us the moisture that makes it possible for the soil to yield food and fiber; its winds bring us comfort or discomfort; it brings us storm and flood and blizzard; we revel in it in fine weather and try to escape from it in bad weather; its moods determine our moods.

Man depends so much on rain that his interest in clouds has always been great. The Babylonians watched the clouds and wondered when the rains would come to flood the Euphrates. Aristotle had a theory about clouds, and every farmer from the beginning of time has tried to tell the weather from the sky. In good weather some kinds of clouds are harbingers of rain; others immediately precede the rains; still others are clouds from which the rains fall; and then there are the tantalizing clouds that appear during droughts. These appear in the late morning or early afternoon, sometimes grow a little, and then flatten out and disappear in the evening without yielding any rain.

The appearance of the clouds has given rise to many weather proverbs, such as:

> "When the clouds are upon the hills,
> They'll come down by the mills."

Each of the climatic zones of the earth has clouds which are more or less characteristic. There are the cumulus and cumulonimbus clouds of the tropics; the fair-weather cumulus clouds of the trade wind belts; the heaped-up clouds of summer and the sheet clouds of winter in higher latitudes. The cirrus forms often precede rain; when general rains are in prospect the high cirrus cloud forms are followed by lowering clouds in sheets, then

rain, and finally by a shift of wind, cumulus clouds, showers, clearing and cooler or colder. (Fig. 63.) These are merely the visible forms of the moisture which is always present in the atmosphere.

The question is often asked: What keeps the clouds up there? Clouds usually are formed in rising air. The air gets colder as it is forced upward until it reaches the temperature where the water vapor condenses. (Fig. 64.) Dry air must rise to greater heights than moist air before the condensation temperature is reached. On any one day, all of the rising air in any given locality has about the same temperature and vapor content, and so the bases of the clouds are all at about the same height. The gently rising current keeps the water particles from falling. If the air begins to descend it becomes warmer and condensation ceases. If the ascending air motion is strong, much condensation takes place. Water droplets accumulate and finally become heavy enough to fall in spite of the rising air. If these vertical motions are exceptionally strong, condensation in the high cold air may produce hail.

Where air is forced up over mountains, there usually are standing clouds. Though the air is in motion, the cloud remains stationary. As the air passes up the slope, it gets colder until it reaches the condensation temperature. Water droplets appear and there is a cloud. As the air passes over the mountain top and starts down on the other side, it gets warmer, condensation ceases, and evaporation begins. Hence the cloud is fixed at the top of the mountain until the wind changes. The appearance or disappearance of these mountain clouds is the subject of many weather proverbs. One of them in Sussex, England, is:

"When Walstonbury has a cap,
Hurstpierpoint will have a drap."

The changes of the wind are associated with general weather changes, so there is value in some of these proverbs, but many of them are just nonsense. Careful observations with instruments are much preferred for weather forecasting.

Occasionally in history, people have kept records of the weather. After the passage of many centuries, instruments were invented

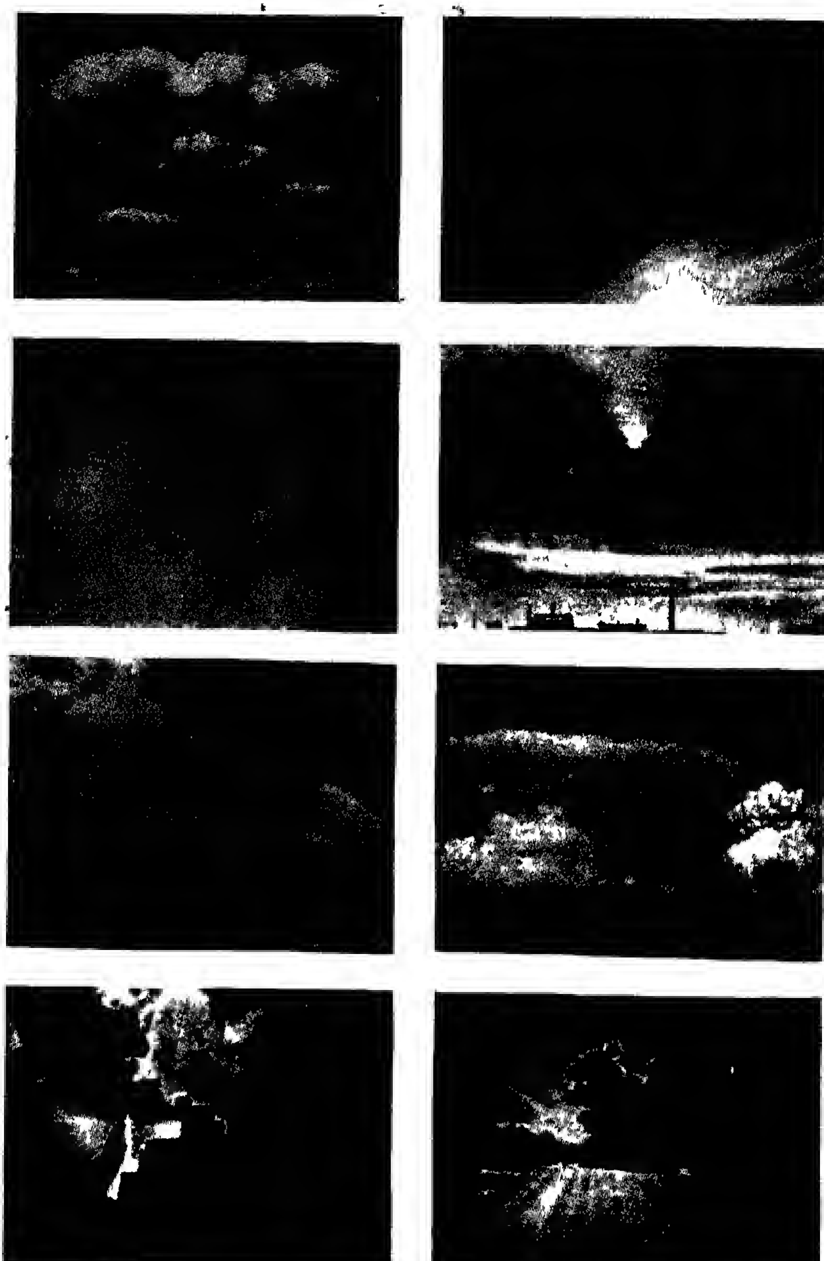


FIG. 63. The rain cycle in the clouds. See description on opposite page.

to measure the temperature, weight, and humidity of the air. Many of the long weather records that are sufficiently good to be worth while were kept by people who got nothing for their labor. War, revolution, political upheavals and other interferences have interrupted or rendered useless many records that would have been of inestimable value if they had been kept with the necessary accuracy and continuity. These records are important because we must try to foresee the future from the past.

So far as we know, the total amount of air in our atmosphere has not changed appreciably since the dawn of history. The human race is destined to live in this atmosphere for thousands of years to come. We ought to learn everything we can about it. We ought to make sure that the vast unknown weather regions of the world are covered by observations, and we ought to persevere in accumulating these records in an accurate form, day by day and year by year until we finally gain a complete understanding of the workings of our atmosphere.

In the meantime, the best we can do is present the picture as

FIG. 63. The rain cycle in the clouds. During drought the skies are cloudless or there are a few small fair-weather cumulus like those shown at top left, perhaps with a few high, feathery, cirrus clouds like those at top right, but by evening the clouds have flattened out like those at the bottom right with the sun's rays and shadows in the dust. When cold air masses come from higher latitudes the rain cycle proceeds as follows: The high thin clouds at top right show the warm air coming in at very high levels above the old cold air. Second from top at left, the warm air comes closer and the high clouds become lower and thicken a little, sometimes with a halo around the sun or moon. Second from top at right, the warm air comes closer and the clouds become lower and thicker (altostratus) toward evening as steady rain begins. It rains all night. Third from top at left, as the rain ceases in the morning the clouds are breaking up with a small bit of open sky showing on the horizon in lower right corner of the picture. The warm air reaches us with clearing skies and the day is warm with high humidity, but (third from top at right) in the afternoon we see thunderstorm clouds in the distance where the new cold air is coming in to push the warm air up and cause showers. Sometimes the new cold air comes in with a roll cloud or a front like that shown in Figure 25. Bottom left, the thundershower of the cold front comes over us and there is heavy rain, lightning and thunder. Bottom right, the clouds flatten out in the evening and the night and the next day or two will be clear or there will be fair-weather clouds like those at the top left until the cycle begins again.

Fig. 64. Cloud cap over Mt. Rainier. (O. P. Anderson photo)

we see it now, filled in here and there by estimate, by shrewd reasoning, or by plain guesswork.

First, we know that it is always hot in nearly all parts of the equatorial regions. The sun goes southward from the equator in our winter and northward in our summer but not far enough at either time of year to make a great difference in temperature near the equator. A line drawn through the middle of this hot strip around the earth is known as the "heat equator." The atmosphere is usually more heated and expanded here than anywhere else on earth.

If we could take a slice through the atmosphere from north to south across the equator as shown in Figure 65, we would find the atmosphere more expanded *north* of the equator in our summer as shown at the left and more expanded *south* of the equator in our winter as shown at the right. In our summer (at left) more air will run down the steeper slope to the south where the air is cold (C) as shown by the large arrow A and less down the northern slope where the air is warm (W) as shown by the little arrow at B.

In our winter the reverse occurs, as shown at the right in Fig-

ure 65. The air is more expanded (W) south of the equator (Eq.) and colder (C) north of the equator. Less air goes down the southern slope as shown by the small arrow at B and much more down the steep northern slope as shown by the large arrow at A.

The air of the Northern Hemisphere expands and sinks more

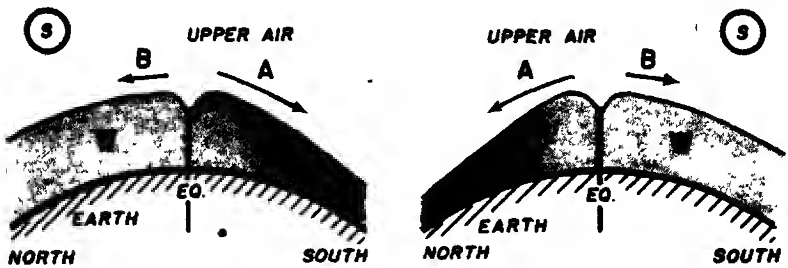


FIG. 65. At left, in summer (sun at S) in the Northern Hemisphere, warm atmosphere (W) is expanded and cold atmosphere (C) in Southern Hemisphere is dense and lies nearer to the earth; air goes more rapidly (A) from equator (Eq.) down the steeper slope toward the South Pole than (B) from equator toward North Pole. At right, in northern winter, air moves more rapidly (A) down steeper slope into Northern Hemisphere than (B) into Southern Hemisphere. By this expansion at the equator and excess flow toward the cold hemisphere, there is a vast exchange of air across the equator.

with the change in temperature between seasons than docs the air south of the equator. This is because there is much more land surface north of the equator and the air over the land gets much warmer in summer and colder in winter than the air over the oceans. Also the difference in temperature between winter and summer is great in the polar regions where the sun is above the horizon all the time in summer and below the horizon all the time in winter.

It is apparent that air accumulates in the Southern Hemisphere in our summer (their winter) and in the Northern Hemisphere in our winter (their summer), because more of the expanded equatorial air flows down the steeper slope into the winter hemisphere. The surface air finds its way back toward the equator to be heated again and start once more around the circuit. By this means a great exchange of air takes place between the two hemi-

spheres every year. In spring, air is going rapidly over to the Southern Hemisphere and accumulating south of the equator as shown at the left in Figure 65. In autumn air is going rapidly over to the Northern Hemisphere and accumulating north of the equator as shown at the right in Figure 65.

There is some evidence to show that the exchange of air between the hemispheres is not of the same magnitude from year to year. There probably are progressive changes of temperature

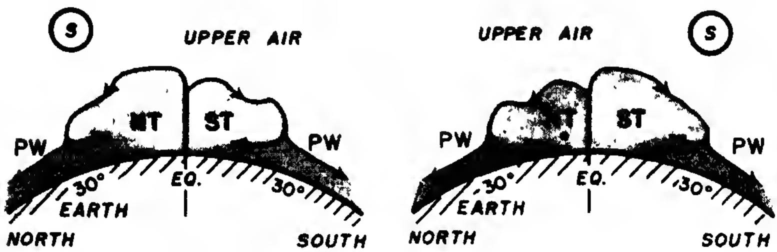


FIG. 66. Same as Figure 65 but these diagrams show how earth rotation causes the overflow from the equator to accumulate in regions of high pressure at about 30° latitude from where the northeast trades (NT) and the southeast trades (ST) blow toward the equator at the surface of the earth while in higher latitudes the prevailing westerlies (PW) blow from the west and incline toward the polar regions

of the oceans north and south of the equator which cause more air to accumulate in the Northern Hemisphere over a period of years and then more in the Southern Hemisphere for a period of years. This exchange of air may have an important bearing on rainfall, but we know very little about it.

The circulation shown in Figure 65 neglects the effect of the rotation of the earth on its axis. But the earth rotates, and every particle of the solid earth must turn with it. Air can move freely over the earth's surface; and when air is in motion, the earth, like a great turntable, moves from under it. The result is that winds in the Northern Hemisphere are turned to the right and winds in the Southern Hemisphere are turned to the left. North of the equator, a north wind is turned to the west, an east wind toward the north, a west wind toward the south, et cetera. This turning

of the winds is called the deflective effect of earth rotation.[26] This introduces complications. One result is that the air tends to pile up at about latitude 30° (Fig. 66) and part of it (NT and ST) flows back at the surface toward the equator and part (PW) due to increased pressure starts again toward the pole but is turned to the right. Here (PW) we have a broad belt of winds moving mainly from west to east or southwest to northeast as shown in Figure 68. Most of the United States lies in this great belt of winds called the prevailing westerlies (PW). The wind belts NT and ST are the northeast trades and southeast trades. Near the North Pole the cold air sinks and flows outward at the bottom, giving the polar wind belt (P) in Figure 68.

The upshot of all this is that our imaginary slice of atmosphere between the equator and the North Pole would actually look more like that shown in Figure 67, where winds marked W blow from the west toward the east, or southwest to northeast, and winds marked E blow from the east toward the west, or northeast to southwest.

At about 30° north and south, where the air tends to pile up, we have high pressure and generally descending dry winds and little or no rainfall. This belt includes the Pacific and Atlantic high pressure areas (Figs. 34 and 59). In these belts of high pressure in the two hemispheres are found most of the world's deserts (Figs. 7 and 10) but the high pressure belts are broken up by temperature contrasts and air circulation between continents and oceans, so there are regions in this belt where there is much rain, for example, in much of southern United States east of the Rocky Mountains.

Figure 68 shows the wind system which tends to develop over the earth, and which would be a uniform pattern if it were not for the differences in temperature between oceans and continents at the different seasons. These ocean-continent contrasts are especially strong in the Northern Hemisphere. In North America, as

[26] The full explanation of the effect of earth rotation involves the principle of the conservation of areas, a component of centrifugal force, friction, and (at any given time and place) the barometric gradient. The speed of the wind is not affected by earth rotation. The effect is directional only.

we have seen in previous chapters, the continent and the mountain system in the west cause part of the prevailing westerly winds to be diverted through Canada and part over the mountains to the southward, and the control of these air streams by the relative temperatures of ocean and continent determines in a large measure the amount and distribution of our rainfall.

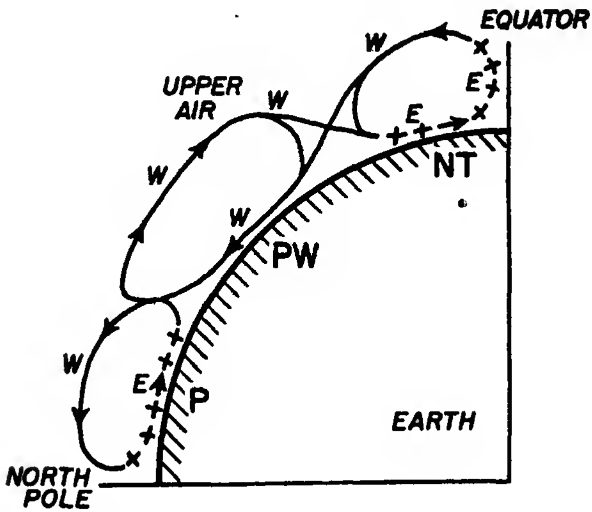


FIG. 67. The circulation shown partly in Figures 65 and 66 is shown here for the entire Northern Hemisphere slice from equator to pole. At points marked W the winds blow from west or southwest and at points marked E the winds blow from east or northeast. The northeast trades are shown at NT, the prevailing westerlies at PW, and the polar easterlies at P. (After Rossby)

Interference of mountains to the prevailing westerlies blowing from the Pacific produces disturbances east of the mountains. This causes warm, moist southerly and southeasterly winds to blow into the United States from the Atlantic and Gulf in place of the surface air of the westerlies, which otherwise would come in greater volume direct from the Pacific. If it were not for the mountains in the west, the prevailing westerlies would carry

moist Pacific air into the interior of the continent and the United States would get its moisture from the Pacific, just as Europe gets its moisture from the Atlantic. A complicated rain machine is needed to make this great detour of the Rockies and bring rain to a vast region that otherwise might be desert.

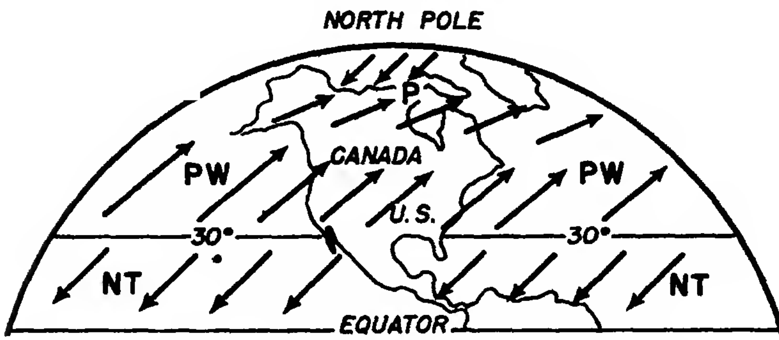


FIG. 68. This is a map of the Western Hemisphere north of the equator showing schematically the surface winds of Figure 67. These are the northeast trades (NT), the prevailing westerlies (PW), and the polar easterlies (P). Oceans and continents cause large day-to-day and month-to-month variations from this schematic wind pattern. It will be noted that the northeast trades blow toward the equator but are turned to the right of their path by earth rotation, becoming northeasterly winds; the prevailing westerlies are winds blowing toward the pole but turned to the right; and the polar easterlies blow from the pole toward the equator but are turned to the right and become northeasterly winds.

To explain fully the distribution of water vapor in the atmosphere around the earth would require more space than we have here. There are many detours on the atmospheric highways, like the detour of the Rockies in North America. But the chief obstacle in the way of a complete description is our lack of observations in many parts of the world. For example, the biggest movement of air in the world is in and out of Asia in summer and winter. There are vast stretches of the interior of Asia where hardly any observations are made and where there are great deserts which do not support a population to maintain observation stations. Likewise, there are vast ocean areas from which we have little reliable information. As long as we lack data on these vast

air movements, our knowledge of the circulation of the earth's atmosphere and the causes of changes in distribution of rainfall will be very sketchy, and we will have difficulty in accounting for some of the changes which affect us so vitally here in North America.

The seasonal changes in the circulation of the atmosphere and the distribution of rainfall do not come in a fixed pattern from year to year. The effects of the Pacific Ocean are not always the same. Droughts do not come regularly. It has been claimed that variations in the sun are responsible for some of these changes. Sunspots give one indication of variations in the sun. Do they affect rainfall? We shall look at this question in the next chapter.

XIII. WHAT ABOUT SUNSPOTS?

DURING periods of deficient rainfall in the United States, we frequently hear that droughts come in cycles. The most frequent claim is that they come in some fraction or multiple of the sunspot period of about 11 years. There is much evidence that rainfall varies in a cycle of about 11 years, and also there are some indications of variations in periods of 22 or 23 years, and in the so-called Brückner cycle which is roughly three times the sunspot period. There is evidence of other cycles, including a short one of about 5½ years. A long cycle often mentioned is 90.4 years.

When we examine the rainfall records in an effort to learn the truth about the effect of sunspots, we find some coincidences and some apparent contradictions. The usual result of these investigations has been the conclusion that these several cycles seem to be worthless for the purpose of predicting droughts and variations in the quantity of rainfall at any one place. The facts must be studied with extreme care, for we have much evidence that the sun is the basic control.

One argument that is presented against the sunspot theory is that the sun could not, for example, pick out Iowa for a drought and at the same time give good rainfall in adjoining states. In 1934 West Virginia rainfall was deficient by 12% while Virginia rainfall was above normal by 10%. In the same year, Georgia and South Carolina were dry while North Carolina and Alabama were wet (Fig. 69). From what has been said in preceding chapters, it is obvious that this argument about the ability of the sun to pick out certain areas is not very convincing. The world's rainfall machine is a complicated affair.

We know that the sun furnishes the power for our complicated rainfall machine, and if the power varies there may be further complications which could easily account for a dry South Carolina and a wet North Carolina in the same year. In the long run, the sun's heat is responsible for all changes in the weather, as the sun rises and sets and goes north and south with the seasons.

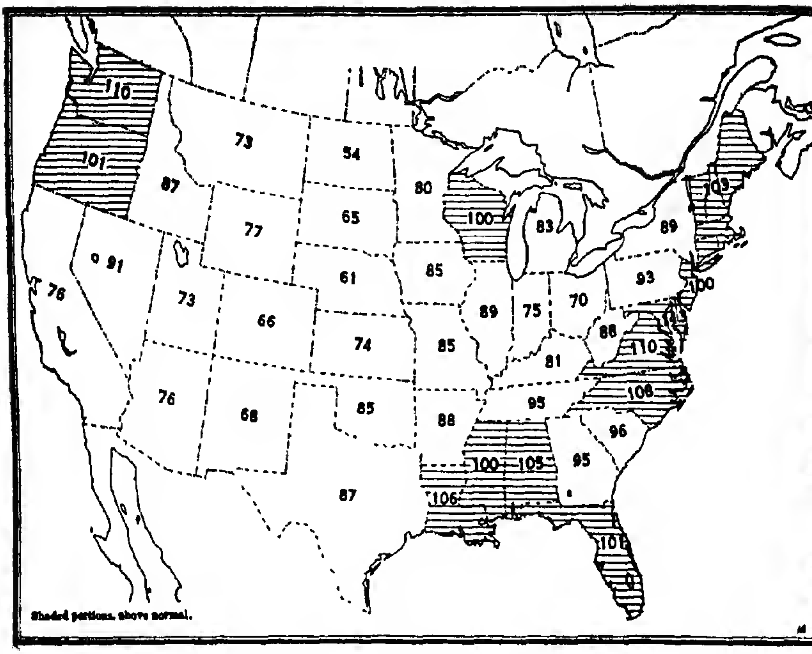


FIG 69 Precipitation in 1934 in percentages of the normal by states (Kincer)

The diurnal effects, and especially the seasonal effects, will afford some clues as to what happens when the sun's radiation changes in a period of eleven years or whatever it may be.

In spring and summer a high percentage of the year's rainfall is carried into the interior of the continent. (Fig. 70a.) The sun is high and the continent warm, and the oceans are relatively cool. In autumn and winter a greater percentage of the year's rainfall occurs in coastal areas or nearer to the coasts than in spring and early summer. When the sun is low, the continent is cold, and the oceans are relatively warm. Therefore, if the sun gets progressively colder from year to year there should be an increasingly lower percentage of rainfall in the interior, and vice versa. There will be many local variations, of course, and the lag of ocean temperature changes will have to be taken into account; but the broad effects should be fairly clear if the sun's radiation changes in an eleven-year cycle, as we believe it does.

Figure 71 at A shows the differences between the national rain-

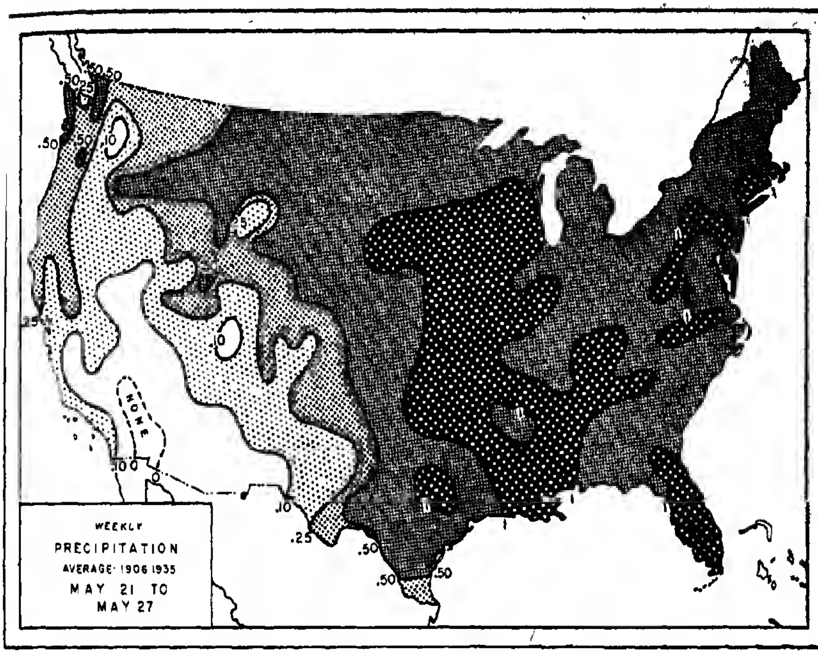


FIG. 70a. Weekly precipitation averages for the years 1906-1935. Week of May 21 to 27. In this map we see rainfall carried northward and northwestward, while the Southwest is dry. Compare this map with Fig. 70b.

fall in the first and second halves of the calendar year. From January to June, the temperature is increasing in most of the United States because of the northward movement of the sun. From July to December it is generally decreasing. The smoothed[27] curve in Figure 71 at A is high when the rainfall of the United States in the first half of the year exceeded that of the second half, and the curve is low in years when the second half of the year had more rainfall than the first half. Curve B in the same diagram shows the number of sunspots. We see that in general when there were numerous sunspots there was more rain in the first half of the year and when there were few sunspots there was more rain in the second half of the year.

[27] Smoothing formula. $\frac{a + 2b + 3c + 3d + 3e + 2f + g}{15} = d'$.

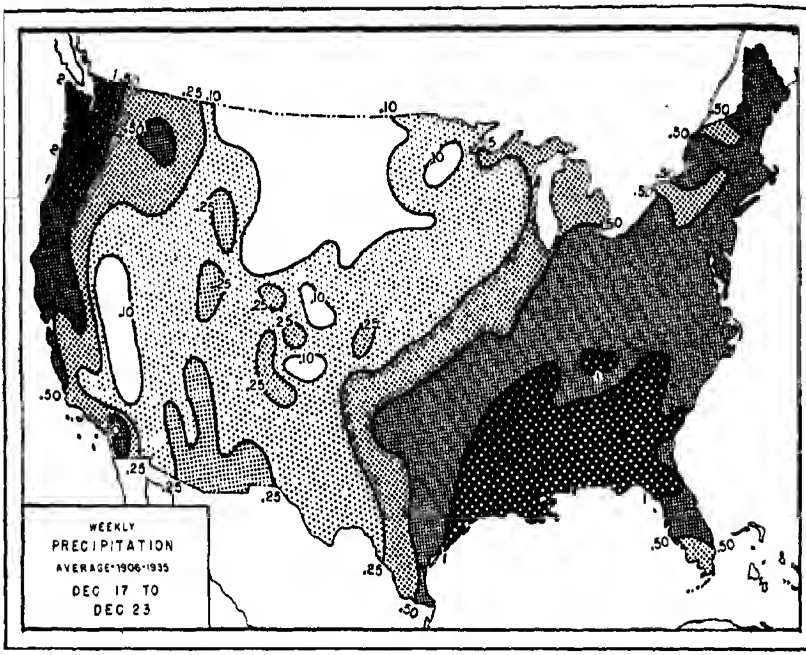


FIG. 70b. Week of December 17 to 23. The rain is heaviest in the Southeast and in the Pacific Northwest. The Northern Plains are dry in the area where cold Canadian air masses are in control. (U.S. Weather Bureau)

The amounts represented in these variations are important. This swing back and forth between the two halves of the calendar year averages about 1½ inches for the nation as a whole, or about 25% of the difference between a very wet decade (1906-1915) and a very dry decade (1930-1939). It will be noted that there is a steady decline in the differences from the early nineties to the early thirties. Rainfall shifted toward the first half of the year with each increase in sunspots but the steady long-period shift was toward the second half.

We have seen already that rainfall varies according to the condition of the Pacific Ocean as indicated by pressures at Portland and other points in the West. How, then, can sunspots also be held responsible? There are two answers to this question. (1) Figure 71 does not show the *amounts* of rainfall; it shows merely the differences between amounts in the first and second halves of

the year. (2) Sunspots also cause variations in the differences of Pacific pressures between the first and second halves of the year. Figure 72 shows an example for the well-defined sunspot cycle, 1901 to 1912. Here we see that pressure at Portland was relatively low in the first half of the year when the rainfall was relatively high in the first half of the year, and vice versa.

It seems clear from Figure 71 that we have two different types

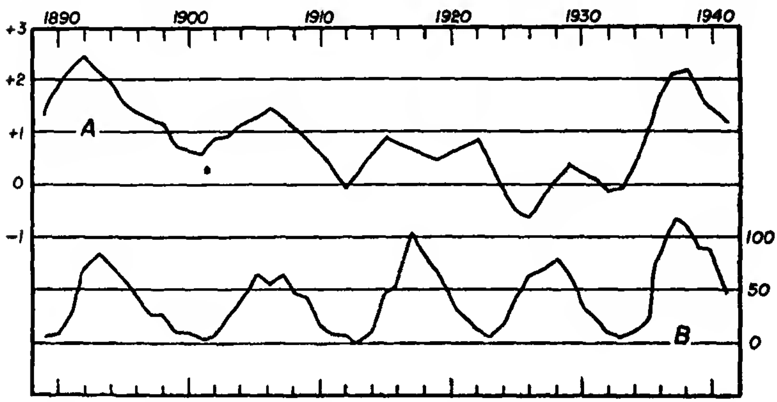


FIG. 71. A. Differences of national rainfall between first and second halves of the year, by scale at left, where positive values show excess in inches in first half of year; negative values show excess in second half; smoothed by formula $\frac{a+2b+3c+3d+3e+2f+g}{15}=d'$. B. Sunspot numbers by scale at right.

of variation to deal with. In the first case, the variations in the sun's heat get immediate response from the continent and resistance from the oceans. This produces the 11-year variations. In the second case, the oceans slowly respond to long-term changes. This produces a slow but steady change or trend in rainfall over a longer period of years. This will be discussed further in Chapter XVI.

As we have noted previously, the temperature differences which carry rainfall into the interior of the United States in late winter, spring, and early summer are owing to (1) the sun's heat and (2) the lag of ocean temperatures. The temperatures of the Pacific

rise in the spring and fall in the autumn at a much slower rate than the temperatures of the continent in the same latitudes. In the same way, the temperatures of the Atlantic and Gulf also rise and fall at a slower rate than the continent. The Atlantic and Gulf, especially the latter, are smaller than the Pacific and consequently their temperatures change more rapidly than the Pa-

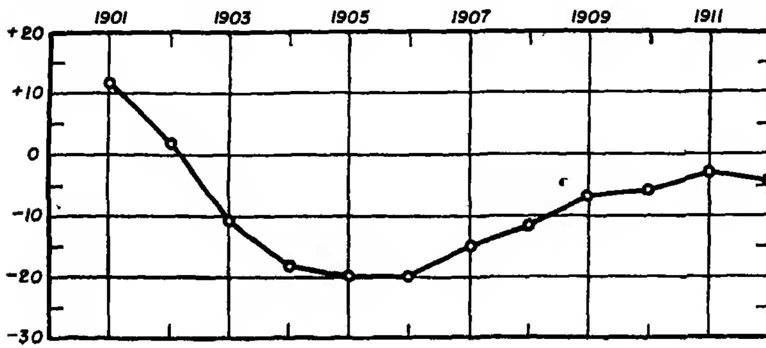


FIG. 72. Differences in pressure between first and second halves of year at Portland, Oregon, 1901 to 1912. Positive values show higher pressure in first half than in second half, and vice versa. Scale at left gives differences in thousandths of an inch. Smoothed by formula given under Figure 71.

cific but less rapidly than the continent. Furthermore, there is a variation in temperature between the eastern and western parts of the oceans (see Fig. 77). These varying temperature differences between the two oceans (and the Gulf of Mexico) introduce a secondary effect which is evident chiefly in changes in the seasonal distribution of the rainfall in the area east of the Rockies.

As an example, Figure 73 shows at A the rainfall at Chicago in April; at B the difference in yearly rainfall amounts between Galveston and Chicago and at C the differences in yearly temperatures between Portland, Oregon, and Bermuda. It will be seen that at or shortly after the time of maximum sunspots shown by an X on the bottom line of the diagram, there is relatively more rain at Chicago. That this is caused partly by the lagging tem-

perature differences between the two oceans is hinted in the third curve (C). (See also Figs. 60 and 86.)

When sunspots are numerous, more of the rainfall tends to go to the interior, including the Great Plains. The swing back and forth between the coast and the Southern Great Plains is illus-

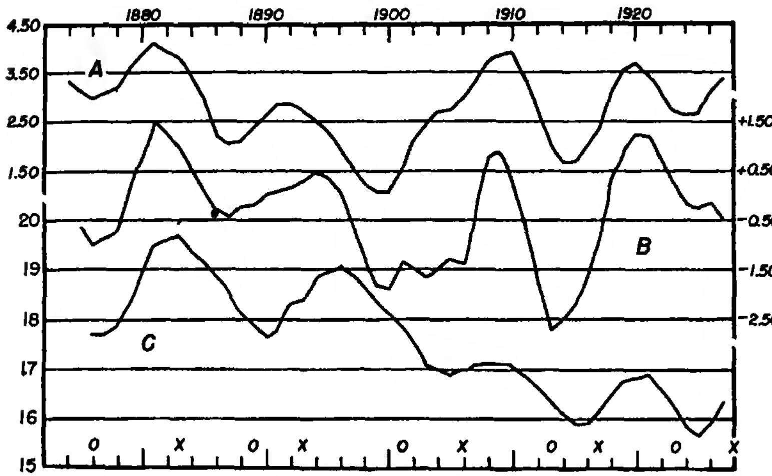


FIG. 73. A. Rainfall in inches at Chicago in April by scale at upper left. B. Differences between April rainfall in Chicago and Galveston by scale at right, where positive values indicate more rainfall at Chicago than Galveston and negative values more at Galveston. C. Differences between annual temperatures at Portland (Oregon) and Bermuda, where Bermuda was warmer than Portland by amount shown on scale at lower left in whole degrees (F.) X on the bottom line indicates maximum sunspots. O indicates minimum sunspots. All values are smoothed by formula given under Figure 71.

trated in Figure 74, showing at A the differences in yearly rainfall amounts between Galveston, on the coast, and Amarillo, in the interior, of Texas (Abilene for the years prior to the beginning of the Amarillo record); and at B the sunspot numbers reversed. At high sunspottedness, the Southern Great Plains get relatively more rain. The difference is very important, with a range of nearly 10 inches per year. But there are definite indications that when the increase in the sun's heat is unusually great,

or when the oceans are relatively colder than usual at time of maximum sunspots, the rainfall is diverted still farther into the interior, and the rainfall at Montreal, for example, is much more than in the Great Plains and Central Valleys. (Chapter VI.)

This shows how the sun can "pick out" certain areas at certain seasons for increased rainfall while adjoining area's have droughts. But the reaction between continent and oceans is complicated. There is no evidence to show that we should expect regular cyclical variations in rainfall at every place in the world, or even anywhere except locally, and then only under favorable condi-

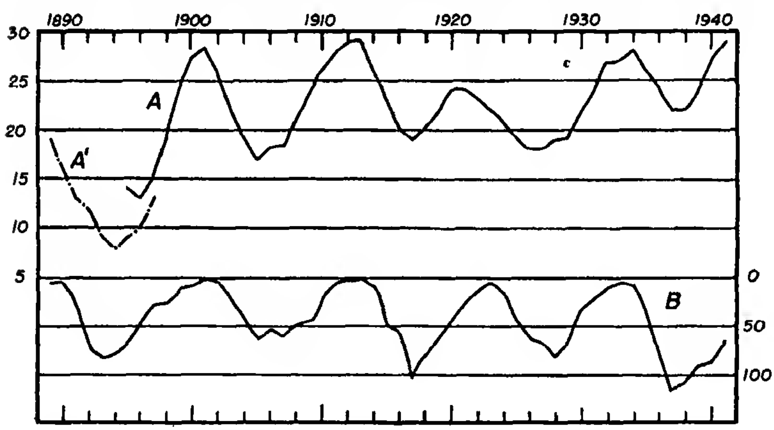


Fig. 74. A. Differences between annual amounts of rainfall at Galveston and Amarillo (Texas). The scale at left shows excess in inches at Galveston. Abilene records (A′) are used prior to Amarillo records, indicated by dashed line. Data were smoothed by formula given under Figure 71. B. Sunspot numbers, inverted, as shown by scale at right.

tions which may be temporary. The relation is best shown by taking differences of rainfall between two places as a measure of the distribution. The broad pattern is controlled by reactions of sun, continents, and oceans; and the timing of these reactions is variable, owing to the different lag effects of the oceans. The reaction between the two hemispheres is also involved.

In all of these curves, the amount of rainfall involved is ex-

tremely important. For example, in the Chicago April rainfall curve (Fig. 73) the extreme variation is about 3 inches, which is roughly equal to the total rainfall at Chicago in an average April.

The varying rates of response of the continents and oceans give us rainfall variations that do not follow exactly the sunspot cycles, but the rainfall curves of the United States, if analyzed properly, seem to fit the broad pattern. Perhaps we can watch the sunspots and predict what our rainfall will be. It may be possible when we know more about it. In the past we have been as badly confused about sunspots as on the drought question. As long as we tried to explain every local or temporary drought in the United States, we were lost in confusion. Students of weather changes have studied local weather records and sunspots and have become confused and discouraged. We must examine the weather records again, omitting details for the present. We must find the main facts in the broad picture.

An Englishman named Harriot has been credited with discovering on December 10, 1610, that there are spots on the sun.[28] Galileo published his paper on sunspots in 1613. Later it was found that the numbers of these sunspots vary in a cycle of about eleven years. After more observations were made, the period was found to average slightly more than eleven years. Actually, the period varies, going as low as seven years or as high as fifteen years. The discovery of the sunspot cycle brought forth the idea that the temperatures on the earth should vary with the number of spots, and many scientists enthusiastically assembled temperature records to prove it. There was great hope that it would be possible to predict the weather far in advance. The investigators expected to find that at maximum sunspots, when the sun is hottest, the atmosphere would be warmer. With few spots and a cool sun, the atmosphere was expected to be cooler. To their astonishment, they found that the opposite was true. At the surface of the earth, where we have all our long weather records,

[28] Some old Chinese records mention sunspots as early as the beginning of the Christian Era and a few references occur in the records of European mediaeval times. For Harriot's record see C. E. P. Brooks, *Climate through the Ages.*

more sunspots bring lower temperatures and fewer spots bring higher temperatures. This fact is fully supported by records in the tropics, where there are fewer violent changes in the weather than in the latitude of the United States. A hot sun makes a cool earth, and vice versa.

This and other complications proved to be so discouraging that nearly everybody abandoned the idea that there might be any direct relation between sunspots and weather. Today there are few workers in this field.

Sunspots (Fig. 3) represent only one activity in the sun. There are other evidences of solar activity, such as prominences, magnetic activity, faculae, and the corona. Records of sunspots are available for a long period of time. The other evidences of solar variation seem to follow somewhat the same course, but the records are by no means so extensive.

Although the number of sunspots varies over a period of about eleven years, this is the smoothed result of all the observations. From day to day and month to month there are shorter-period variations. Abbot and Clayton have discussed some of the shorter-period variations in the sun and the weather on the earth. The relations are complicated and difficult to follow through from cause to effect. Much remains to be done, both in obtaining records of the sun's variations and in tracing the effects in the earth's atmosphere.

In the study of drought we can smooth out most of the shorter-period changes in sun and weather. Drought takes considerable time to develop. In that respect it differs from most other changes in the weather. If we can understand the effects of the 11-year variation in the sun we will have a good basis for understanding the longer and shorter variations.

Why should a hot sun make a cool earth? A number of meteorologists have offered a simple answer to this question. Some consider it too simple to be acceptable. We can put it this way: A farmer comes into a cold room and starts a fire in a stove. Heated air from the stove is forced upward to the ceiling by cold air in the room. The warm air spreads out along the ceiling. Cold air flows along the floor toward the stove to replace the warm air

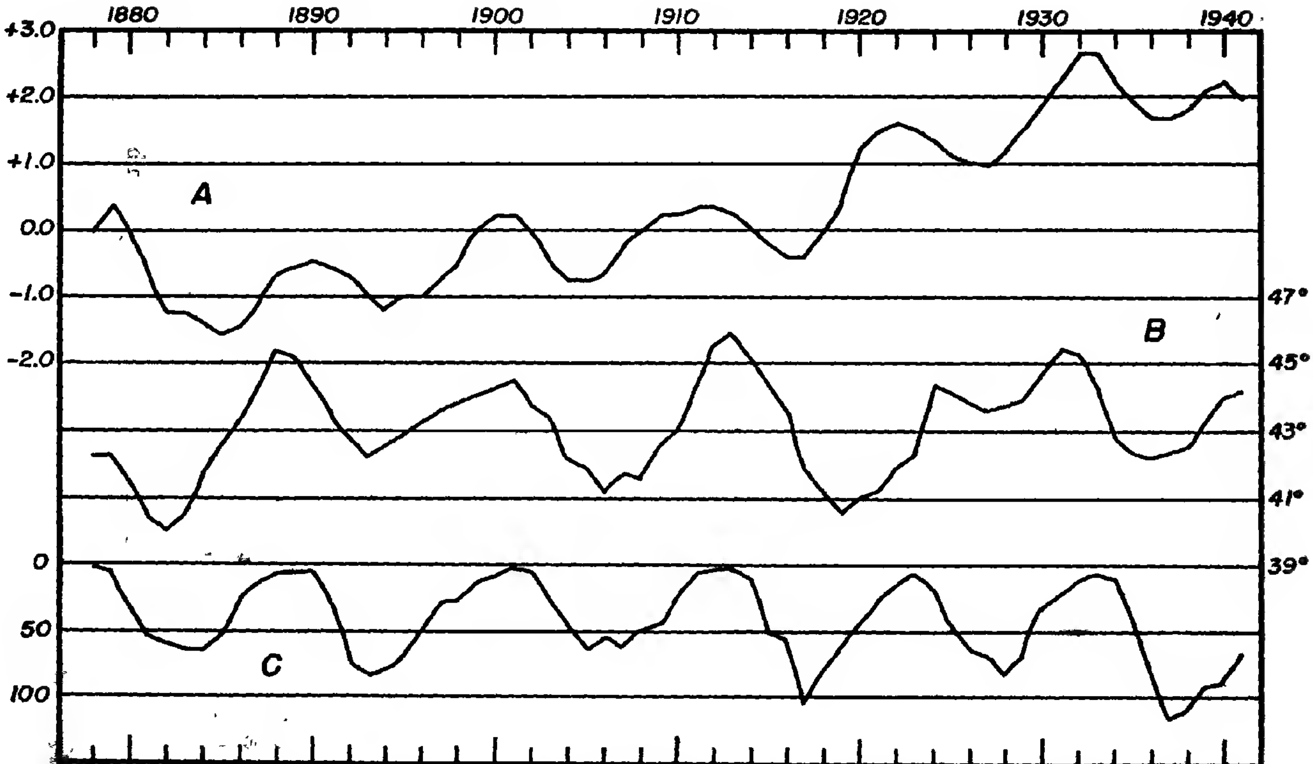


FIG. 75. A. Annual temperature departures (F.) from normal at Bismarck by scale at upper left. B. April temperatures at Bismarck by scale at right. Temperatures smoothed by formula given under Figure 71. C. Sunspot numbers inverted; scale at lower left.

pushed upward. The farmer faces the stove but his back and feet feel cold. If you ask him for an explanation, he gives you a simple one. He says he "feels a cold draft on his back."

When the sun gets hotter, more warm air is forced upward in the equatorial regions. It flows toward the poles in the upper air. Soon it becomes cold and begins to find its way back toward the equator over the earth's surface, just as the cold air in the room comes back along the floor toward the stove.

Figure 75 shows at A the yearly temperatures at Bismarck, North Dakota, from 1875 to 1944. C is the inverted sunspot curve. North Dakota is in the area where cold air comes southward in the great channel east of the Rockies. Every time the sunspots increased it became colder at Bismarck. Figure 75 at B shows the same thing for April at Bismarck. When sunspots go up the temperature in the area goes down. The people at Bismarck "feel a cold draft from Canada."

Of course, there are some irregularities, and the curve had to be smoothed to show this regular result. But the April curve shows that this "draft from Canada" is important. April temperatures go up and down by several degrees. Most of the time they stay well above freezing, but in cold years the temperature is likely to go below freezing, and occasionally they drop below zero.

In the center of the continent (Bismarck) we see that a "hot sun makes a cool earth." This rule also applies to the lower stratum of air over much of the earth. When more air goes up in the equatorial regions more air must find its way back from pole to equator at the surface.

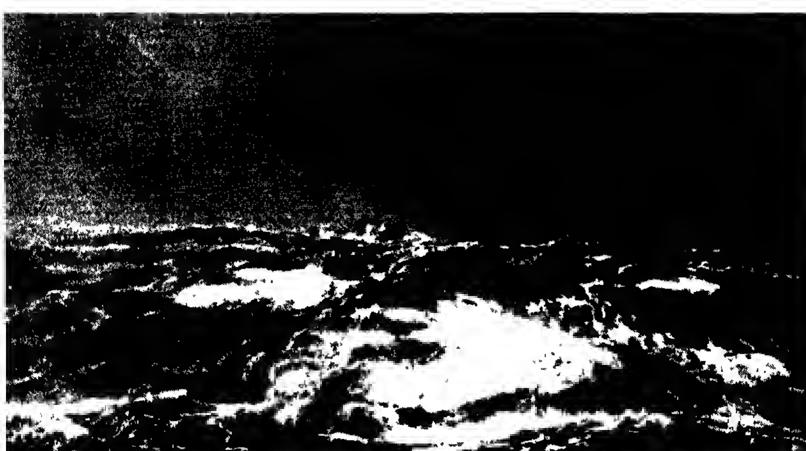
The farmer knows that when the fire in the stove begins to die down, and the air in the room has become warm and the coals burn low, the draft on his back becomes weaker and he is comfortable without holding his feet to the fire or standing with his back to the stove. When sunspots become fewer, the air at the earth's surface feels warmer. We know that this change also affects our rainfall. We need a certain amount of cold air from Canada to make rain. Conditions may be favorable, except that the great Pacific Ocean sometimes lags behind. It will be interesting to take another look at this ocean-temperature relation before going further with the discussion of sunspots and rainfall.

XIV. WHAT MAKES THE OCEAN COLD?

We have seen how high Pacific pressures and relatively cold ocean waters accompany drought, and we have looked at some of the processes which account for failure of the rains. The next question is: What makes the oceans colder in some years than in other years?

Warm air does not make the ocean warm; cold air does not make the ocean cold. The heat required to raise a cubic foot of water one degree is more than 3,000 times the heat required to raise a cubic foot of air one degree. Therefore, the temperature of the air has very little direct influence on the temperature of the oceans. On the other hand, air which blows over the ocean soon takes on the temperature of the ocean surface. If cold air blows out over a warm ocean, the air quickly becomes warmer and is forced upward by colder air which in turn becomes warmer and is forced up. When warm air blows out over a cold ocean, it gets colder and heavier and tends to remain close to the ocean surface.

Although air temperature has little effect on the oceans, air movement causes important changes in ocean temperatures. Wind, especially when strong, makes waves and mixes the warm surface



'ɪɢ. 76. Strong winds mix the waters of the ocean and distribute the heat to considerable .epth. (U.S. Navy photo)

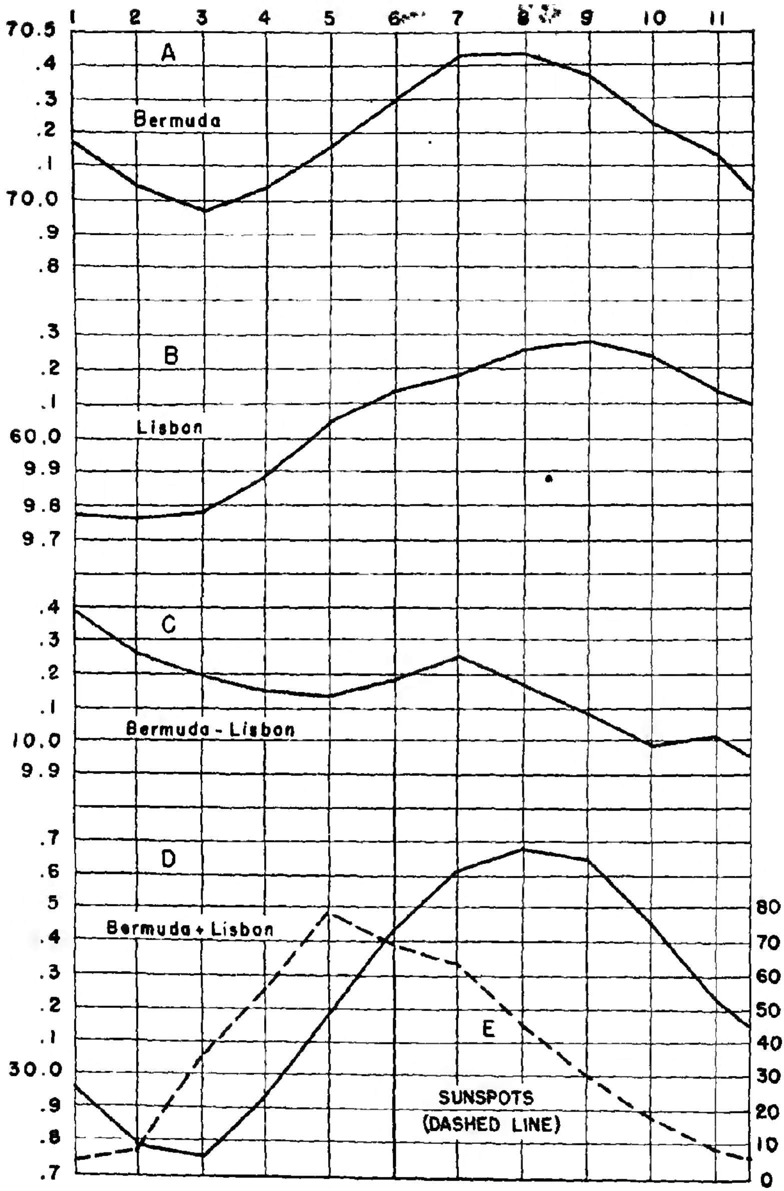


FIG. 77. Smoothed temperatures data for averages of four sunspot cycles beginning in 1878, 1889, 1901 and 1913 for: A, Bermuda; B, Lisbon; C, difference between Bermuda and Lisbon; and D, sum of Bermuda and Lisbon; E, average sunspot numbers, dashed line. Scales at left show temperature (F.) in degrees and tenths. Data smoothed by formula given under Fig. 71.

of about two years behind sunspot minimum and a lag of about three years after sunspot maximum.

The differences in annual temperatures (1873-1930) between Bermuda and San Diego are shown in Figure 78. We see several broad oscillations of the type which seem to be caused by lagging ocean reactions to solar changes in the sunspot period. Here we see the western Atlantic (Bermuda) becoming progressively cooler with reference to the eastern North Pacific (San Diego). Such a change would cause more rainfall in the interior of the United States for a period of years. The cooler Atlantic would cause the rain to go into the interior and the warmer Pacific would cause more frequent cold air from Canada to produce precipitation. If this progressive change would continue long enough, the rainfall in the United States would cease to increase and would finally begin to diminish, because the cooler Atlantic temperatures would cause the moist currents to go still farther inland, with more rain in Canada and less in southern and southeastern coastal sections of the United States. The progressive changes described above represent approximately what has been happening in the United States since the beginning of the national rainfall records shown in previous chapters.

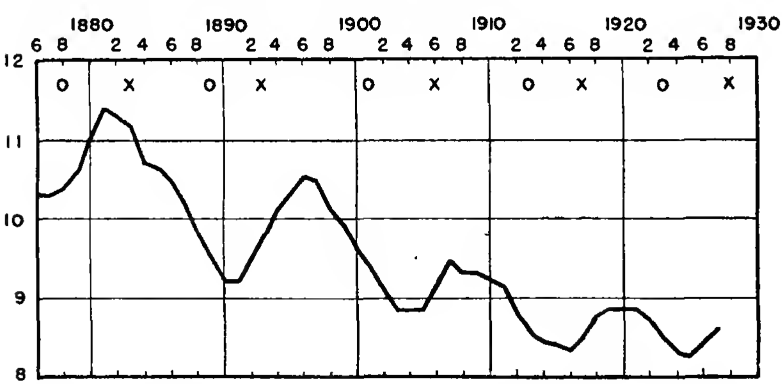


FIG. 78. Smoothed annual temperature differences between Bermuda and San Diego. Scale at left shows excess temperature of Bermuda over San Diego in whole degrees (F.). Smoothing formula given under Figure 71. At top of diagram, X's show times of maximum sunspottedness; O's show times of minimum sunspottedness.

When we begin to examine ocean temperatures we find the same sort of confusion that we found in the case of drought and sunspots. There is much conflicting evidence.

It has long been known that the Florida current, the Gulf Stream, and the relatively warm North Atlantic Drift have a profound influence on the climate of Europe. The prevailing westerly winds carry warmth and moisture from the Atlantic to western and northern Europe in winter and also act in summer to prevent extremely high temperatures there. The winters, more than other seasons, are responsible for variations in the yearly average temperatures, and it is much warmer on the average in western Europe than in the same latitudes in the eastern parts of the United States and Canada.

Before 1900 there was much speculation about the effect of changes in the Gulf Stream on the weather of Europe. This was a matter of such importance, especially to the people of northern Europe, who live in the same latitude as Labrador and southern Greenland, that there was a strong incentive to study the temperatures of the Atlantic and find a basis for predicting the weather well in advance. First it was necessary to collect information on ocean temperatures.

We learn about the temperatures of the oceans chiefly from observations taken on board merchant ships while they are on regular voyages across the oceans. In past years there have been two methods of getting ocean temperatures on shipboard. The first method is to throw a bucket overboard and draw in a sample of the surface water. The temperature is taken by holding a thermometer in the water until it comes to the water temperature. There are several objections to this method. One is that the wind over the sea and the wind caused by the ship's motion induce evaporation and cooling while the sample is being taken. By the other method, a thermometer is placed in the intake which brings water to the ship's engines so that the temperature of the water can be measured as it comes into the ship. One trouble with this method is the variable depth of the intake of ships. Some are close below the surface while larger ships have the intake far down in the water. The depth also depends on the weight of cargo.

The advantages and disadvantages of these two methods have been the subject of long discussions without any definite conclusions. The truth is that the only really accurate way to get ocean temperatures is by using specially equipped vessels on oceanographic expeditions, but this is an almost impossible task so far as the ocean weather problem is concerned. The oceans are vast, and a few oceanographic expeditions provide interesting but only fragmentary data.

Beginning about 1900, European scientists enthusiastically examined the accumulated ocean-temperature observations from ships in the Atlantic, trying to find a correlation with European weather. Many long and technical works were written. Endless contradictions increased the confusion. The problem has not yet been solved satisfactorily.

One of the facts that bothered the investigators was the cold Atlantic water in 1903 and 1904. There seemed to be no good reason why the North Atlantic should be so cold at that time. The depression of temperature was greatest in the western part of the North Atlantic. The northwestern part of the ocean has a cold Labrador current which comes into contact with the Gulf Stream near the Grand Banks of Newfoundland. This current carries much cold water and ice. (Fig. 103.) There was an uncommonly large amount of ice in this current in 1903. But the evidence was not clear that this current caused the temperature depression.

Helland-Hansen and Nansen made one of the best reports on the subject. A reprint containing more than 400 pages was published in 1920 by the Smithsonian Institution. The authors concluded that "the winds are the principal cause of temperature variations on the surface and in the air upon the North Atlantic." They found that at times the wind blows more continuously than usual from northern directions bringing cold air masses and cold water southward.

To find a simple solution we remember sunspots—and the farmer with his stove. The cold water was not caused directly by the ice, or the temperature of the air, or the Labrador current; all were produced by the same cause, a "draft" from the polar regions. In 1901 there was a sunspot minimum. There is much evidence

that it was an unusually cold one. In 1903 and 1904 solar radiation was rapidly increasing, judging by the increasing number of sunspots. More than the usual amount of equatorial air must have been coming northward at high levels in spring of those years. The circulation of the atmosphere was strong, and more than usual cold air was finding its way southward at the earth's surface. Helland-Hansen and Nansen noted that much of the world was cold, and there were colder waters than usual in other parts of the oceans.

While the Europeans were trying to solve their weather problems by studying the Atlantic Ocean, meteorologists in the United States were not much concerned about the Pacific Ocean. We did not believe that our rainfall east of the Rockies could be affected to any great degree by Pacific temperatures. Beginning about thirty years ago weather students in the United States became greatly interested in Atlantic temperatures. Many of our investigators thought that unusually warm or cold Atlantic waters might affect the weather along the east coast. It turned out that the wind movement and not the air temperature affects ocean temperatures. But it now seems that the effects of ocean temperatures are by no means confined to the coasts, as was thought thirty years ago. Ocean temperatures influence the weather profoundly over the whole earth. Our inquiries in the past have been entirely too restricted.

There is much evidence to support the conclusion that when the circulation of the atmosphere becomes more vigorous because of changes in solar radiation, the winds tend to lower the temperature of the ocean surface by mixing, and stronger winds increase the circulation of ocean waters, creating a greater temperature oscillation between the eastern and western parts of the ocean. These changes certainly affect the amount of distribution of rainfall on the continents.

If the variations of the sun's heat in the sunspot cycle are responsible for changes in ocean temperatures and in all temperatures in the earth's atmosphere, why is it that cold oceans and droughts do not come at fairly regular intervals like the sunspots? We will have to examine the weather records again.

XV. DO DROUGHTS COME IN CYCLES?

IF we select the years in the United States with national rainfall less than 95% of normal, we find that in the 58-year period between 1886 and 1944 there have been fourteen such dry years, 1893, '94, '95, 1901, '10, '17, '24, '25, '30, '33, '34, '36, '39, and '43. If we consider the groups '93-'95, '24-'25, '30-'31, and '33-'36, each as a single especially persistent drought, we have a total of nine droughts in the period beginning in 1894 and ending in 1943, averaging one every five or six years. But there has been little regularity. Some drought years have come close to the top of the sunspot cycle (1893 and 1917), some near the bottom (1901 and 1933), some with increasing spots (1925 and 1936), and some with decreasing spots (1910 and 1930). No matter how we select the years or how we group them, we see no obvious relation to sunspots. We know that the distribution of rainfall is related to solar variations (Chapter XIII), and that cold or relatively cold Pacific temperatures and national droughts are associated, but it appears that national dry years come and go at random.

Random variation in Pacific temperature and occurrence of drought seems to be entirely contrary to everything we know about the reaction of the atmosphere to seasonal and other changes in the heat received from the sun. Let us look at the records again, but first it may be wise to go once more into the cold room with the farmer and the stove. Let us suppose that the coal stove has been replaced by a gas stove which can be turned up and down. At the proper time we shall put a pile of ice at the side of the room opposite the stove. The ice represents the north pole and the stove will do for the equator. We suppose that the stove will heat the room perceptibly in a few minutes, and the room will cool perceptibly in a few minutes after the stove is shut off. To compare with the sunspot cycle we shall consider the time to be 11 minutes. The notes regarding our experience with the farmer in the room might be as follows:

0 Minute. The room is distinctly cold—a still cold—with very little air circulation.

1 Minute. The stove is turned on with a low fire. It feels slightly more comfortable both from radiation of heat from the stove and slight increase of temperature of the air.

2 Minutes. The stove is turned up a little and it feels slightly warmer.

3 Minutes. The stove is turned up more. We feel a little warmer but we note a draft cross the floor toward the stove.

4 Minutes. The stove is turned up more. There is a distinct movement of cool air across the floor toward the stove carrying the warm air away from us. We turn our backs to the stove and hold our hands behind us. It is not so warm.

5 Minutes. The stove is going full blast. There is a stronger draft toward the stove and the air it brings feels slightly cooler.

6 Minutes. The stove is turned down a little. The draft has decreased a little. The air feels warmer.

7 Minutes. The stove is turned down a little more. The draft subsides somewhat. The air in the room is warmer.

8 Minutes. The stove is turned off. The draft diminishes. The air feels warmer.

9 Minutes. The air feels slightly cooler.

10 Minutes. The air is definitely cooler. There is a slight draft from the direction of the ice.

11 Minutes. The room has cooled to its original temperature.

Looking back over these notes we see that we felt warmer in the 3rd minute and again in the 8th minute, and we felt colder in the 5th minute and again in the 11th minute. There was a double effect which was the combined result of changing air temperature and the change in air circulation. While the air temperature in the room actually might not show all these variations, we would feel these changes, just as the oceans do not become much colder, but circulation and mixing produce such an effect relative to the continental temperatures.

March is often cold and windy as the sun crosses the equator coming northward, and although September is likely to be warm and quiet as the sun crosses the equator going southward, it

generally becomes cold and windy again by November. In the same way we may find a change in air circulation and rainfall in the 11-year cycle. Figure 79 shows at A yearly pressure differences between Portland and San Diego from 1886 to 1944, smoothed, and at B the national yearly rainfall (inverted scale) 1886 to 1944, also smoothed.[29] Here we see an irregular variation averaging about 5 or 6 years. Each point marked D indicates a national dry year or the beginning of one or more dry years in succession. (See also Fig. 80.)

This suggests the following ideas. Increasing sunspots and increasing solar activity in the sunspot cycle cause a more vigorous circulation in the spring of the year. The increased circulation, together with the more rapid rise of temperature over the continent than over the ocean, causes the Pacific high to be especially strong. Increased circulation causes stronger ocean currents, mixes the ocean waters, and eventually brings cooler water southward into the region west of California. The ocean as a whole is actually getting warmer, but the motion of the wind and water makes it relatively cooler, like the 5th minute in front of the farmer's stove.

As solar radiation diminishes, the ocean finally gets cooler; and once again the Pacific high builds up. It seems to depend on the rate of change in solar radiation.

For the time being, this must be regarded as mainly guesswork. We do not have enough observations from the Pacific Ocean to treat the problem accurately. But we can examine the records to see if the rainfall of the United States is in agreement.

We may expect two conditions. First, if our idea is correct, the relative coolness of the Pacific which comes with increasing solar radiation will develop in the spring when the sun is coming northward and will continue into summer as the ocean circulation persists. Second, if the ocean actually becomes cold in high latitudes because of diminishing solar radiation, this will occur in autumn and winter and may even persist into spring. But it will not persist into summer, because in decreasing sunspot years the

[29] $\frac{a+b+c}{3} = b'$.

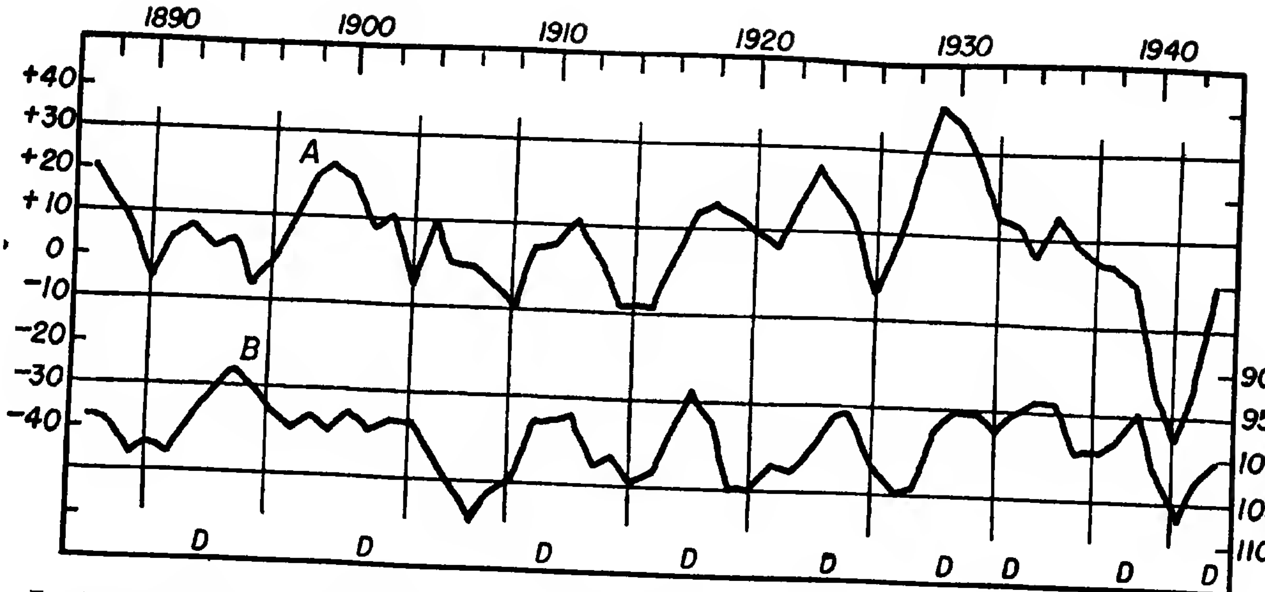


FIG. 79. A. Annual pressure differences between Portland and San Diego, smoothed $\frac{a+b+c}{3}=b'$. Scale at left shows differences in thousandths of an inch. Positive values indicate Portland pressure higher than San Diego pressure, and vice versa. B. National rainfall in per cent of normal, smoothed in same manner as A. Scale at right is per cent of normal. Letter D at bottom indicates a dry year with rainfall less than 95 per cent of normal, or the beginning of a series of one or more such years. Variations in A indicate changes in intensity of the Pacific high. See Figure 83.

sun will be relatively weak, and the continent will not be so warm compared to the ocean as in increasing sunspot years.

Figure 80 shows at A national rainfall, smoothed, for the months of April and May. Times of sunspot maxima are shown by X's at the bottom of the diagram; sunspot minima by O's. Here we see that rainfall diminishes as sunspots *decrease*. At B we have the national rainfall for September, at the end of the period of development of the summer high off the Pacific Coast. Here we see that rainfall diminishes as sunspots *increase* and that rainfall is deficient at and a year or two after sunspot maximum. At C we have the differences between the national rainfall in spring (April and May) and in early autumn (September). Here we see an extraordinary effect of solar variations in the sunspot cycle. These smoothed variations *average 20% or more of the national rainfall*, and the extreme (curve C of Fig. 80) swing is *more than one-third of the national rainfall.*

This suggests that there are two kinds of droughts on a national scale. One kind develops in summer and autumn in years when solar radiation is great or rapidly increasing, and the other kind develops in winter and spring in years when solar radiation in the sunspot cycle is low or rapidly diminishing. In the colder half of the year droughts develop on the Pacific Coast as rainfall diminishes there, and at the same time or in the following year they may spread across the United States. In the warmer half of the year we cannot see droughts developing on the Pacific Coast, since there is very little rain there in summer under any conditions.

We have a relatively short rainfall record to use in checking these ideas, but there is another way of finding out. Rainfall variations are shown by the rings in the big trees of California and Arizona and also in other parts of the world. Tree rings give us some data extending back more than 3,000 years. A few of the trees now living were young saplings at the time of the great drought and famine when Joseph was in Egypt and during the Exodus of the Hebrews. Certainly many of these trees were living during the days of the Roman Empire, and still more in the succeeding centuries of early European history.

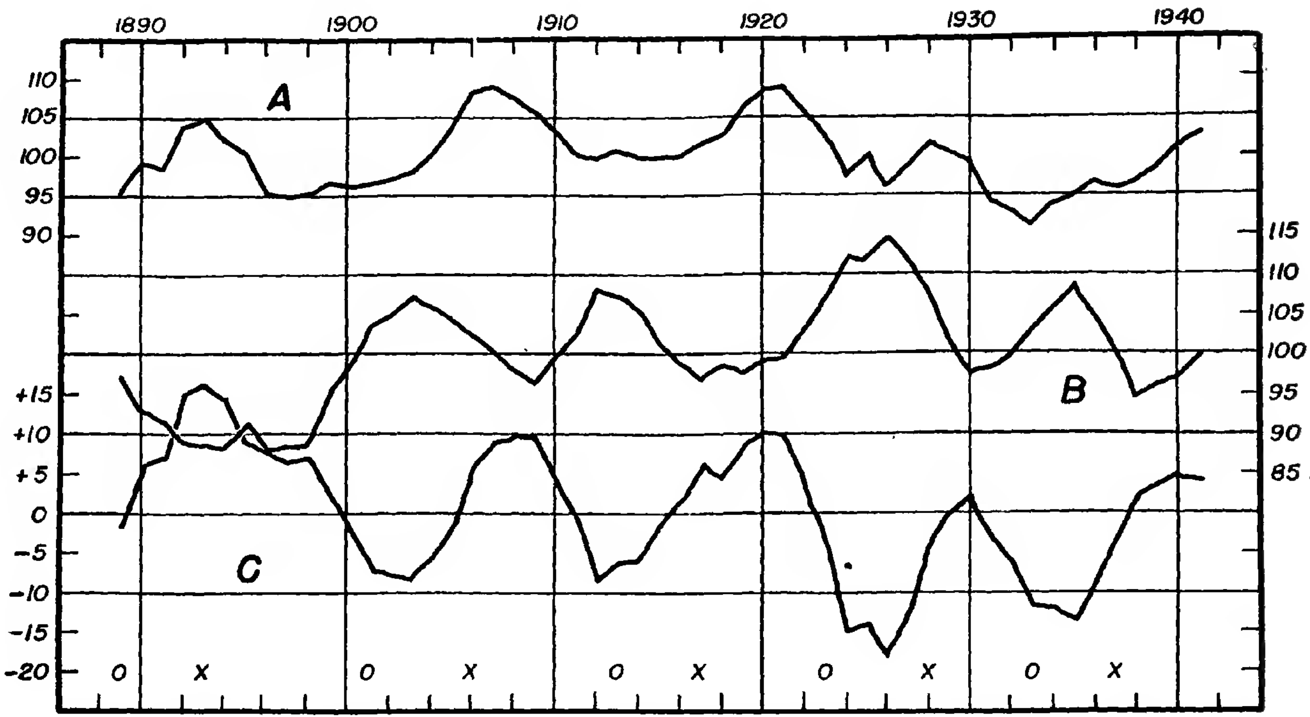


FIG. 80. A. National rainfall for April and May in per cent of normal, scale at upper left. B. National rainfall for September in per cent of normal, scale at right. C. Differences between A and B in per cent, scale at lower left. Positive values show more rainfall in April and May than in September, and vice versa for negative values. All data smoothed by formula given under Figure 71. At bottom of diagram X's and O's show times of maximum and minimum sunspots, respectively.

Douglass[30] pioneered the important work of studying tree rings to get an estimate of the rainfall in past centuries. His studies of tree rings began in Arizona in 1901. In later years he studied trees in other areas, particularly in Europe. Huntington[31] also made important investigations in this field.

Space does not permit a full discussion of the methods of measuring rings or of correlating them with rainfall. The facts are briefly as follows: The growth of the tree is usually shown by a ring for each year. (Fig. 81.) The year of growth is considered to begin in the autumn. When rainfall is plentiful the annual rings are large; in dry periods they are small. The corresponding rings of different trees can be identified, that is, a ring in one tree in the year 1800 can be identified by a ring in the same year in another tree. These rings show the 11-year solar cycle.

Figure 82 by Douglass shows smoothed records of sunspots and growth of Arizona pines with a cycle one-half the sunspot cycle.[32]

There is a great deal of evidence that there are two principal temperature and rainfall variations during the 11-year sunspot cycle. They are caused by seasonal changes in the circulation of the atmosphere combined with solar variations. Turn again to Figure 80. If we consider the April-May rainfall and the September rainfall separately we see that the effect on the annual rainfall at any one place will be a tendency toward double variation; these two variations may combine in the annual amounts to give us two maxima and two minima in each sunspot cycle. It varies, of course, with the rate of change of sunspots and the length of the sunspot period.

There is good reason to look for a national dry year about once every five or six years. When rainfall tends to be generally deficient, we have two or more dry years in one spell; and when rainfall is generally heavy, the drought is less serious. We have had droughts in 1886-87, 1893-95, 1899-01, 1904, 1910, 1917, 1924-25,

[30] Douglass, A. E., *Climatic Cycles and Tree Growth.* Publication No. 289, Carnegie Institution of Washington, 1919.

[31] Huntington, Ellsworth, *The Climate Factor.* Carnegie Institution of Washington, 1914.

[32] The tree rings show a 5½-year cycle owing to rainfall sub-oscillations, as explained in Chapter XVI.

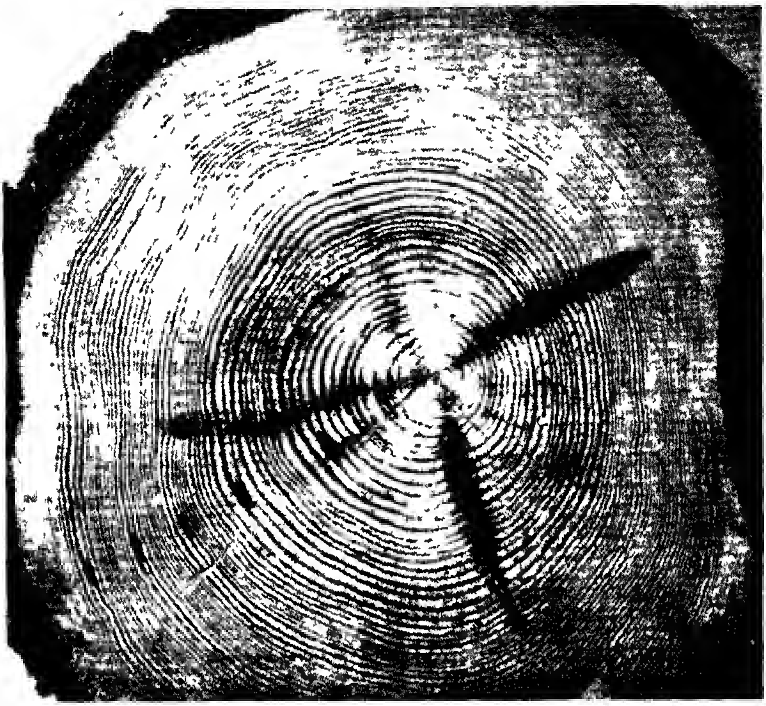


FIG 81 Section of Scotch pine from Eberswalde, Prussia, showing annual rings Arrows point out indications of the solar cycle (By permission of Carnegie Institution of Washington)

1930-31, 1934-36, 1939, and 1943. The average interval is 5.65 years, which is very close to one half the sunspot period, but there is much irregularity.

Because of lack of data from the oceans and the polar regions, the explanation cannot be fully established. The circulation of the atmosphere provides good reasons for a cycle equal to about half the sunspot period. First we have increasing heat with the tropics getting warm more rapidly than the polar regions, and second, we have decreasing heat with the polar regions getting cold more rapidly than the tropics. The circulation is driven by relative temperatures. When the temperature contrast is great, the effect is

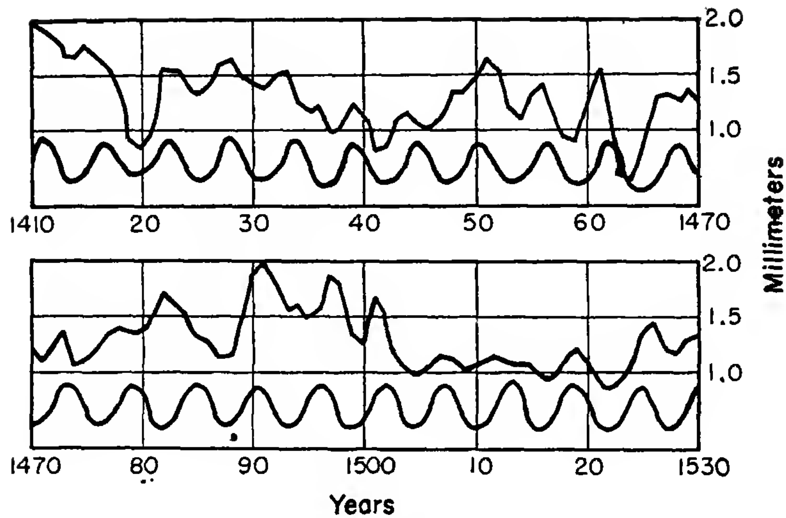


FIG. 82. Growth of Arizona pines (upper curves) in a cycle one half the sunspot cycle (lower curves). (By permission of Carnegie Institution of Washington)

the same regardless of the direction of absolute temperature change. This produces a quickening of the circulation[33] twice during the sunspot cycle. Because of the several variable factors, including variations in the solar cycle, the seasonal effects, and the lag of ocean temperatures, we can hardly expect great regu-

[33] In discussing variations in the strength of the circulation of the atmosphere, it is assumed that when the temperature contrasts between the equator and the polar regions are greatest, the circulation is strongest, and vice versa; and also it is assumed that both the meridional circulation as shown in Figure 66 and the horizontal circulation as shown in Figure 68 are affected in the same manner, but this second assumption is by no means satisfactorily demonstrated. It is probable that in the usual sequence of events the meridional circulation increases first, accompanied by a temporary "choking" of the horizontal circulation over the relatively cold surface (continent or ocean, depending on the season) and that the increase in the horizontal circulation (west-to-east in the prevailing westerlies) does not become fully established until the returning surface branch of the meridional circulation has reached the tropics. The surface branch reaches the tropics through an intensification of the trades (summer) or an intensification of the continental anticyclone (winter). At present the nature of these processes is almost altogether a matter of speculation.

larity. The complications are obvious when we realize that the rise of solar radiation in a new cycle, short or long, may begin while the sun is south of the equator, north of the equator, or crossing the equator in either direction, and that each of these events would bring a slightly different sequence of conditions in the ensuing years. Add to this the variability in the length of the sunspot period and the probable variations in actual intensity of solar radiation, and we have a difficult problem. But the main features of the rainfall variations are beginning to emerge.

The complete solution of this problem will have to wait until more data are accumulated. In the meantime, we can watch the rise and fall of our national rainfall from year to year and feel confident that it certainly is not just a random combination of rainless or rainy days. We may hope for a better understanding in the future.

XVI. TRENDS AND OSCILLATIONS

Although there are certain variations in the distribution of temperature and rainfall which appear to be caused by changes in solar activity, the changes of temperature and rainfall from year to year in any one place appear to be quite irregular, with no clear relation to the number of sunspots. But further study has brought out certain characteristic features which are found in temperature and rainfall data in all parts of the world. For example, consider the annual temperatures at Bismarck, North Dakota, near the center of the North American continent. The average annual temperature at Bismarck during the period from 1875 to 1944 was 41°. In Figure 83 the irregular line A shows the temperature (unsmoothed) at Bismarck for each year during this period. It will be noted that there were exceptionally high yearly temperatures in 1878 and in 1921; and in general after 1930 the temperature was high. Incidentally, there were widespread droughts in many parts of the world in 1921 and in 1877-78. The year 1921 was a dry year in the United States but 1878 was not. The years from 1930 to 1939 were dry in the United States.

The simplest form of smoothing was used to get the Bismarck temperature data for the curve marked B. The average temperature for each successive pair of years was assigned to the second year of the pair. For example, the average temperature for 1875 and 1876 at Bismarck was plotted for 1876; the average for 1876 and 1877 was plotted for 1877, etc.

With some of the irregularity removed by smoothing, in curve B we see rather clearly a double variation with a strong tendency for two maxima and two minima in the sunspot cycle. The dashed vertical lines are drawn through years of maximum sunspots. The tendency toward two maxima in curve B between each pair of these dashed lines is clear. Some of the variations from year to year (curve A) are caused by such occurrences as severely cold weather which may come before or after midnight of January 1,

thus giving proportionately greater weight to one year or the other.

In curve C the type of smoothing used for the Bismarck temperatures is designed to remove the effects of the double cycle and show more clearly the relation to the full sunspot cycle. The formula used is $\frac{a+2b+2c+2d+2e+f}{10}=d'$. The value derived by this method of weighting 6 successive values is assigned to the fourth year.

Here (C) we have a definite variation corresponding to the sunspot variations (E) with lower temperatures at or slightly after sunspot maximum and higher temperatures at sunspot minimum. But there is another variation which is now very clear. It is the slow trend upward throughout nearly all of curve C.

Curve D in Figure 83 is derived by taking the average temperatures for eleven successive years at Bismarck and using that average as the value for the last year. For example, the eleven yearly temperatures from 1875 to 1885, inclusive, are averaged and the average is plotted for 1885. This method places each average about 5½ years later than its actual mean position in time, but this is the usual practice in plotting "moving averages," as they are called. It will be seen in curve D that the double variation appears again, as this type of smoothing tends to remove the 11-year variations but not the fairly regular shorter-period variations.

In curve D the main feature is a progressive rise in temperature from about 1885 to 1944. Actually this rise takes place from about 1880 to about 1939 if we consider the values assigned to their approximate mean positions. Such trends occur in all parts of the world; and when properly identified in their relation to continental and oceanic influences, they seem to be in harmony with the theory that they represent the effects of long-term changes in solar radiation modified by the lag effects of the oceans. Evidence of such trends may be seen in Figures 71, 73, 74, 78, and 80.

In meteorological literature there is no standard terminology for these several types of variations. For the sake of clarity, we must establish a suitable terminology. In Figure 83 there are

variations from year to year which are more or less irregular. Some of these are caused by the seasonal changes which combine to make the annual values; and as previously remarked, there are also some irregularities caused by the division of winter at midnight between December 31 and January 1. Part of the same winter's temperatures are used in two different calendar years. All of these variations from year to year will be included in the general term "variation," as it is used in this book. Variation refers to any kind of change, without regard to its cause or nature.

In curve B of Figure 83 we see a distinct type of variation which is irregular but has roughly a period of five or six years. It seems to be approximately half the sunspot period. It appears rather definitely that (Chapter XV) the rise of solar radiation with increasing sunspottedness causes equatorial temperatures to rise faster in spring than temperatures in the polar region, where the rays of the sun are not effective until about the vernal equinox. The sun does not come above the horizon at the North Pole until late in March. The hotter the sun is, the greater is the temperature contrast between the equator and poles at this season. This in turn causes a depression of temperature at Bismarck because of the surface return of air from the north, the "draft" from Canada.

The second variation in each sunspot cycle is evidently caused by decreasing or low solar radiation with decreasing or few sunspots. The atmosphere as a whole is losing heat. In the autumn and winter the polar regions lose heat more rapidly than the equatorial regions. The sun is farthest north in the latter part of June and thereafter it approaches the equator, crossing it in September going south. It is then directly overhead at the equator, but the sun is going below the horizon at the North Pole, and the long nights in the Arctic are beginning to merge with a sunless winter. During all of that time, up to late December, the polar regions are losing heat faster than the equatorial regions The greatest contrast develops at the time when solar radiation is diminishing in the sunspot cycle or is low near a sunspot minimum. This causes an increase in the flow of air from equator to poles

and a depression of temperature at Bismarck owing to the surface return.

At Bismarck during nearly all of this period of record the surface return at sunspot maximum has been the dominant movement, and when the curve is smoothed (curve C) the secondary minimum tends to disappear.

There seem to be two variations caused by the sunspot cycle, and the greatest effects will come in years when the rate of rise or fall is greatest. If there are pronounced irregularities, the result will be different. For example, if the increase in solar energy is rapid, then slower, then more rapid again, there may be two impulses in the first half of the sunspot cycle. Generally, the

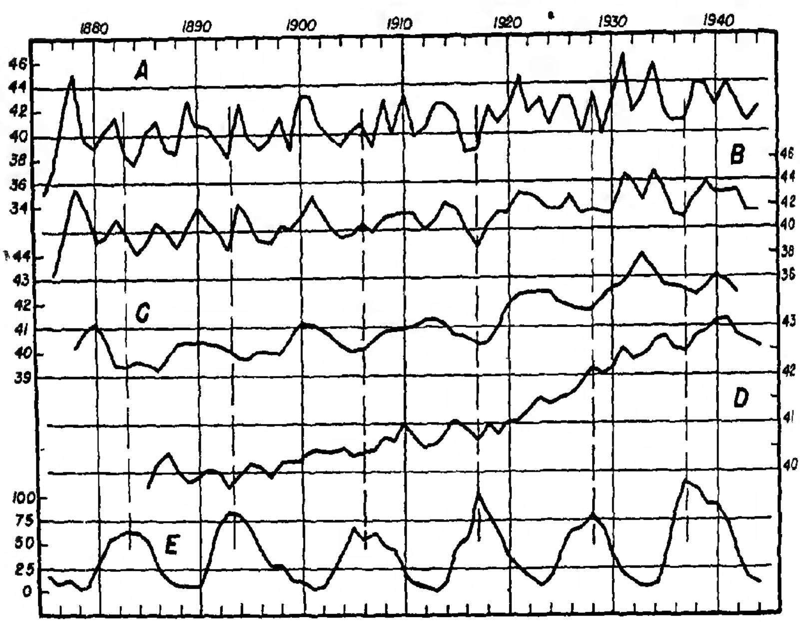


FIG. 83. A. Unsmoothed annual temperatures at Bismarck, N. Dak., with scale in degrees (F.) at upper left. B. Bismarck annual temperatures smoothed $(\frac{a+b}{2} = b')$, with scale at upper right. C. Bismarck annual temperatures smoothed $(\frac{a+2b+2c+2d+2e+f}{10} = d')$ with scale at middle left. D. Eleven-year running means of Bismarck annual temperatures, with scale at lower right. E. Sunspot numbers with scale at lower left. Dashed vertical lines show occurrence of maximum sunspots.

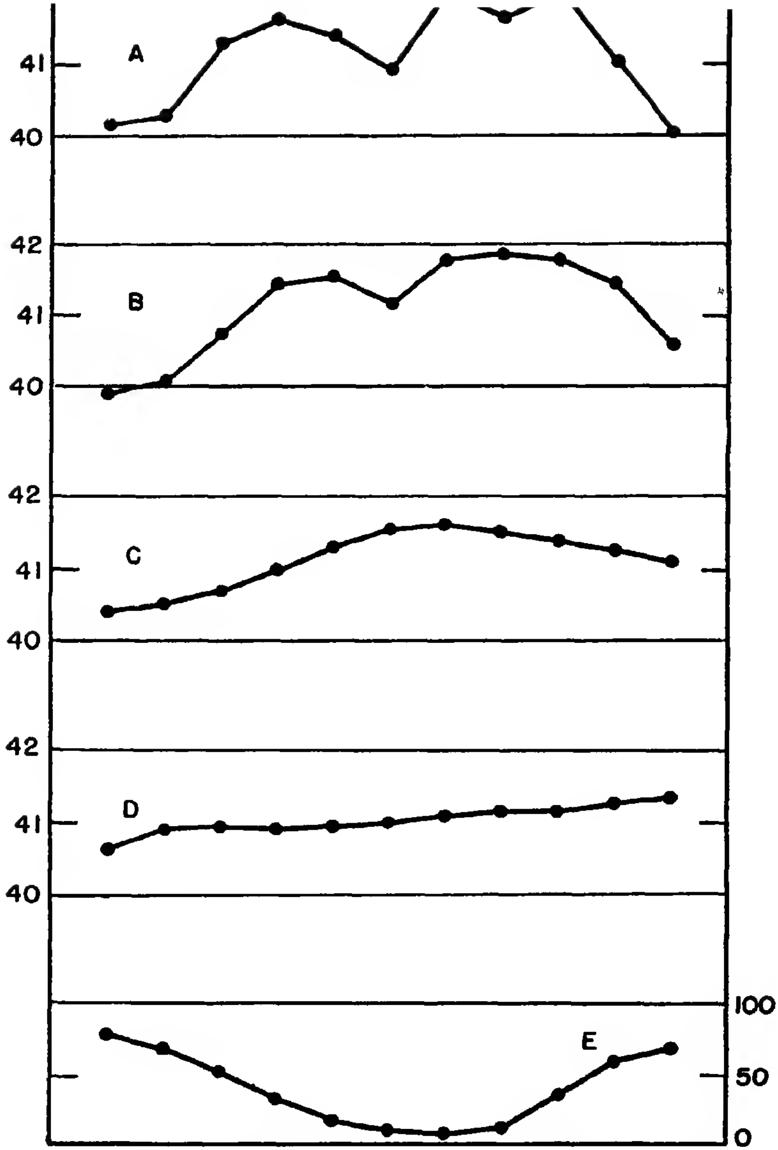


FIG. 84. Curves A, B, C, D, and E are the averages of values in curves A, B, C, D, and E of Figure 83, for five sunspot cycles beginning with a maximum sunspot year in 1883, 1893, 1906, 1917, and 1928. Curves A and B show the cold sub-oscillation in years 1 through 5 and the warm sub-oscillation in years 6 through 11. Curve C shows the full 11-year oscillation, and curve D shows the trend. Curve E shows the sunspots.

changes in sunspots, and presumably the solar variations, are sufficiently regular to produce two fairly definite sub-cycles.

These two variations, or sub-cycles, occur at about twice the frequency of the sunspot cycle. If we use the term "oscillation" to describe one complete variation during the sunspot cycle, then the term "sub-oscillation" should adequately describe a variation which is completed in about half the sunspot cycle. To differentiate between the two sub-oscillations, we shall refer to the "warm sub-oscillation" and the "cold sub-oscillation," indicating increasing or decreasing sunspots. At the earth's surface both are cold; but in the warm sub-oscillation, the temperature of the whole atmosphere is actually rising. The wind from north to south created at the earth's surface makes it feel cold.

As the oceans respond slowly to increasing solar radiation, the warm sub-oscillation subsides and the air begins to feel warmer. The warm sub-oscillation is controlled by the oceans and is developed chiefly in the first half of the calendar year.

The cold sub-oscillation is dominated by radiation of heat from northern land areas and is developed chiefly in the second half of the calendar year. North-to-south motion increases again in the surface air. The air is colder, and cold winds blow southward.

Figure 84 shows the curves A, B, C, D, and E of Figure 83 averaged for the five sunspot cycles beginning at the times of maxima as year 1 in 1883, 1893, 1906, 1917, and 1928. The depression owing to the warm sub-oscillation is evident in year 1 in curves A and B, and the depression owing to the cold sub-oscillation in year 6. Curves C and D show the trend, but C shows clearly the 11-year oscillation.

In Figure 85, A and B of Section 1 are two places in the interior of the continent. We can consider B to be Bismarck and A to be a point in Canada some distance to the northward. Suppose the normal temperature at A is 30°, at B 40°. Let us suppose that during the warm sub-oscillation the temperature of the air rises 4°. But owing to north-to-south motion, A's air with a temperature of 34° moves down to B and colder air from farther north moves down to A. Actually the temperatures are A 24°, and B 34°. (Section 2 of Fig. 85.) The temperature of the air continues to

rise, but the north-to-south motion in the warm sub-oscillation subsides. The temperatures reach 37° and 47° (Section 3) under the hot sun.

In the cold sub-oscillation the temperature of the air falls and the north-to-south motion results in the temperatures (26° and 36°) shown in Section 4. As the motion of the air in the cold sub-oscillation subsides, the temperature of the air rises gradually as shown in Section 5. Then, with the beginning of the next warm sub-oscillation, the air starts to flow and the cycle begins again.

Figure 85 is simply a schematic diagram. There is no significance in the temperatures given. The diagram merely illustrates effects of air motion.

These ideas have led to the use of the following terms:

Variation—Any change in the weather, whether regular or irregular, regardless of its cause.

Oscillation—A variation which is completed in the sunspot cycle. It may have sub-oscillations.

Warm sub-oscillation—A variation which takes place during the period of increasing spots in the sunspot cycle.

Cold sub-oscillation—A variation which takes place during the period of decreasing spots in the sunspot cycle.

Trend—A long-term variation, of the order of twenty to fifty years or more, which is caused by a progressive increase or decrease in solar radiation more or less independent of individual sunspot cycles.

Although an increase in solar radiation in the warm sub-oscillation causes temporarily lower temperatures, an increase in solar radiation in the trend will cause higher temperatures in the long run. The two produce opposite results because the ocean resists the short-period change in the oscillation but responds slowly to the long-period change in the trend.

The oscillations and sub-oscillations in the temperatures at Bismarck are important. They give an indication of the flow of cold surface air from Canada into the United States through the northern plains; and this cold air, as we have seen, is one of the important factors in producing rainfall in the United States. In the intermediate warm periods between the sub-oscillations there is

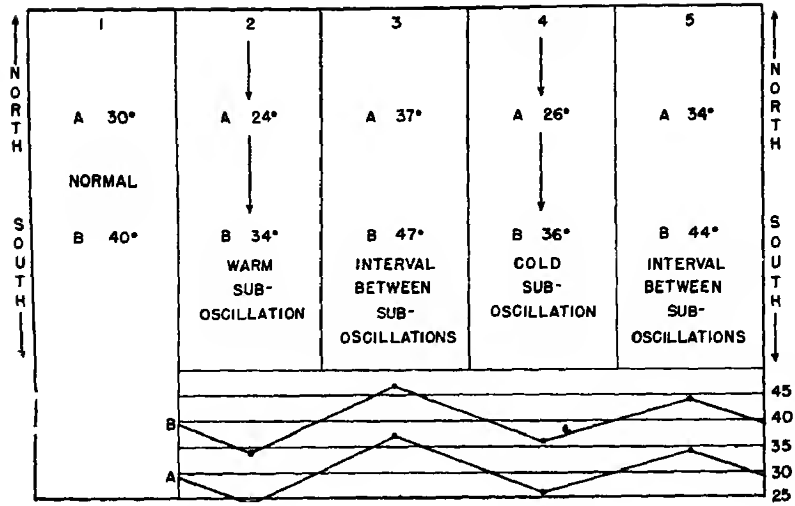


FIG. 85. Above, Section 1, A and B are two places with normal temperatures 30° and 40°, respectively. In Section 2, the temperature of the air mass rises 4°, but movement from north to south results in temperatures of 24° and 34°, that is, the air at A now with a temperature of 34° moves down to B, and air from farther north with a temperature of 24° comes down to A. In Section 3, the air cools slightly but the lowering caused by north-south movement subsides, the air heats slightly and temperatures are now 37° and 47°, respectively. In Section 4, the north-south component of motion increases and temperatures are 26° and 36°. In Section 5, the movement subsides and temperatures rise to 34° and 44°, after which they fall slowly to 30° and 40° as the warm sub-oscillation begins. The two curves in the lower part of the diagram show the temperature variations at A and B during the two sub-oscillations. In Figure 84 the depressions of temperature in the 1st and 6th years in Curves A and B are sub-oscillations corresponding to Sections 2 and 4 above.

likelihood of drought, because persistently cool oceans lag behind the cold of the sub-oscillations while temperatures are rising on the continent.

We have seen already (Fig. 71) that there is a variation of rainfall in the United States between the first and second halves of the calendar year. Cold winds from the north cause rain in the half-year in which they predominate. During the warm sub-oscillation there is more rain in the first half of the year, and in the cold sub-oscillation there is more rain in the second half of the year.

When we treat rainfall on a yearly basis we observe the two sub-oscillations, and we find an irregular period of about five or six years. Droughts tend to occur at intervals between the two sub-oscillations, but of course they are influenced by the rate of rise and fall of solar radiation and the ocean temperatures.

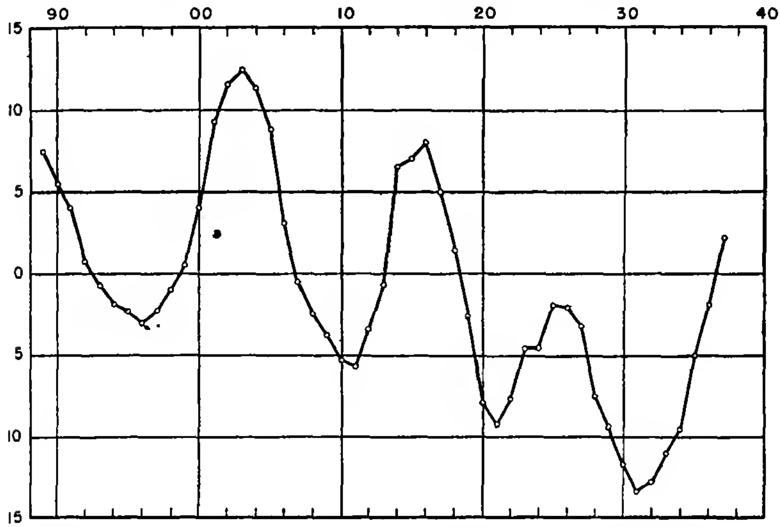


FIG. 86. Differences in annual rainfall between Wisconsin and Louisiana, expressed in percentage of the normal average for each state Positive values show Wisconsin rainfall to be in excess of Louisiana rainfall, and vice versa for negative values. Values smoothed by formula given under Figure 71.

In the midwestern part of the United States, rainfall is controlled partly by the wind circulation which arises from relative Pacific temperatures and partly by the north-south distribution, which is related to both Pacific and Atlantic and Gulf temperatures. Here again we find an oscillation and a trend.

Figure 86 shows the differences between annual rainfall in Wisconsin and Louisiana. These are state averages expressed in percentage of the normal. Here we see the oscillations with the sunspot cycle, and the trend. The curve has been smoothed to remove sub-oscillations and shorter-period variations. Although the differences of temperature and pressure attending these

changes are slight when compared with day-to-day changes, the rainfall variations are large. In Figure 86 the total swing in rainfall amounts to more than 25%.

The variations in rainfall caused by the two sub-oscillations have appeared in the growth of trees as shown by tree rings and other data. They have disturbed many investigators, and the appearance of trends in addition to sub-oscillations has given rise to the belief that there are many cycles which may or may not be independent of variations in solar radiation.

The following remarks summarize the findings of some of the leading investigators in rainfall cycles:

McEwen (1934) had some success in making seasonal rainfall forecasts for California from departures from normal of sea temperatures at La Jolla during the years from 1916 to 1934. A five-year cycle in California rainfall was found to be especially prominent. He thought that the greater the intensity of the high pressure area over the ocean during the summer, the greater would be the rainfall during the following rainy season. He used the ocean temperatures as an index to pressure distribution and the expected rainfall.

Meldrum (1872) showed that the rainfall at tropical stations varies directly with the sunspots, with a maximum of rainfall at a maximum of sunspots. Other investigators at about the same time got similar results. Archibald and Hill showed that winter rain in India exhibits the reverse relation, that is, there is more winter rain at time of sunspot minimum.

Archibald (1900) said, "There is thus a double periodicity of drought and famine in North India and a single periodicity in South India in the sunspot cycle. . . ."

Schreiber (1903) found a variation in rainfall in Europe with the sunspot cycle but with two maxima and two minima in each sunspot cycle (two sub-oscillations).

Buchan (1903) found a double period (two sub-oscillations) in England. Hellmann (1909) found that in most cases there are two maxima and two minima of rainfall in the sunspot cycle. Wallén studied rainfall and lake levels in Sweden and came to the same conclusion.

Douglass (see Chapter XV) found evidence in tree rings of a double period in rainfall in the United States (two sub-oscillations) which were best shown in the records from about A.D. 1420 to 1670 and from A.D. 1790 to the present. (Fig. 82.)

It has been the general conclusion that there are two sub-oscillations of rainfall in the sunspot cycle, but no good reason was advanced for the existence of such sub-oscillations. This rather irregular double period served to discredit much good work because it was not understood. There was the further difficulty that the temperature changes seemed rather small, and the rainfall variations were so complicated that the magnitude of changes of rainfall with solar variations was not fully evaluated.

Some have thought that trends of the type shown in Bismarck temperatures in Figure 83C and especially the recent general upward trend in temperatures in the United States may be artificial. The clearing away of the forests, cultivation of the land, construction of highways and airports, and the growth of cities, may have caused changes in the climate of the United States. There are now large areas with soil exposed to the sun where formerly there were forests and thick undergrowth, and in these forested areas it was cooler in summer than at present. If these changes have had a significant effect on the climate, and especially on the distribution of rainfall, it is obvious that man can control the climate. If the trends have not been caused in any important degree by the work of man, we must attribute them to progressive changes in the sun, or the temperature of the oceans, or the circulation of the atmosphere, or several of these influences acting together. These questions will be discussed in the next two chapters, "Can We Control the Climate?" and "Is Our Climate Changing?"

XVII. CAN WE CONTROL THE CLIMATE?

WHENEVER there is a serious and prolonged drought in this country, various questions regarding control of climate arise in the minds of hundreds of thousands of people who are affected by the lack of rainfall. Nearly all of these questions are variations of one main question, "Can we control the climate?" There are many who say that we can, and many others who say it is impossible. Both answers are partially right.

Probably the main function of civilization is to shield human beings from the discomforts of climatic environment. We spend a very large share of our time in this effort. Houses, clothes, and fuel are basic necessities. Clothing is designed to trap a small part of the atmosphere surrounding our bodies and make that small part of the atmosphere comfortable. The type and quantity of clothing we wear are determined by the climate. In New York in winter the average man wears about fifteen pounds of clothing, designed partly for comfort and partly for appearance. It is not a very efficient combination, but we think it looks well, and it is easy to get on and off. He spends a good share of his time in taking off and putting on articles of clothing so as to be comfortable both indoors and out. A significant share of his earnings is spent on clothes, fuel, and housing. The importance of protection from the climate has been emphasized during the recent war and in the post-war period, when there were shortages of these three essential commodities.

The Eskimo wears about ten pounds of clothing efficiently designed to keep him comfortable in a much colder winter climate than that of New York. At a temperature of 5° below zero, the New Yorker is likely to feel very cold in his fifteen pounds of climatic control; the Eskimo gets along with his ten pounds at 50° below zero. In hot weather the Chinese depend on light, loose clothing, and a hand fan.

In our buildings we trap a larger part of the atmosphere. By burning fuel we attempt to make that larger portion comfortable

From this standpoint, the design of buildings is highly important. The building of the Eskimo has a low broad door that releases little warm air as he goes in and out. The southerner tends toward high ceilings, tall doors, and high windows to keep the warm air above him and let it out as soon as there is cooler air to replace it. The New Englander has a steep roof to let the snow slide off, but his windows are smaller and his ceiling lower to keep the warm air closer to the floor.

Closed automobiles with heaters, air conditioning in hotels and on trains, and electric fans are other methods of controlling a small amount of atmosphere.

In cool climates these activities keep civilization hustling. Clothing is produced by the important wool and cotton industries. The building industry also is a big one. These industries provide employment for millions of people. A vigorous climate is a stimulus to everyone to find better ways of controlling the small parts of the atmosphere in which we live. In tropical climates the problem is relatively simple. The stimulus is lacking. The most highly organized civilizations are generally found in vigorous climates with changeable weather.

We also attempt to control the temperature of the free air out of doors with some success. We heat orchards in cold weather. (Fig. 87.) We cover vines and other vegetation on cold nights to control the temperature of a small amount of atmosphere and prevent damage by frost.[34] Of course, this is done mostly on still clear nights when shallow pools of cold air are formed near the ground. This does not provide any way of heating, or otherwise controlling, the temperature of any large portion of the free atmosphere.

In time of prolonged drought, ideas about artificial control of climate take two forms. Some believe that acts or practices of man cause failure of the rains or can modify the effects of lack of rainfall. Others suggest that we can produce rain artificially.

An example of the first case is the widespread belief that destruction of forests has caused a change of climate. A humid

[34] The smoke produced by the so-called "smudge pots" is a by-product, having only nuisance value. Only the heat produces favorable results.

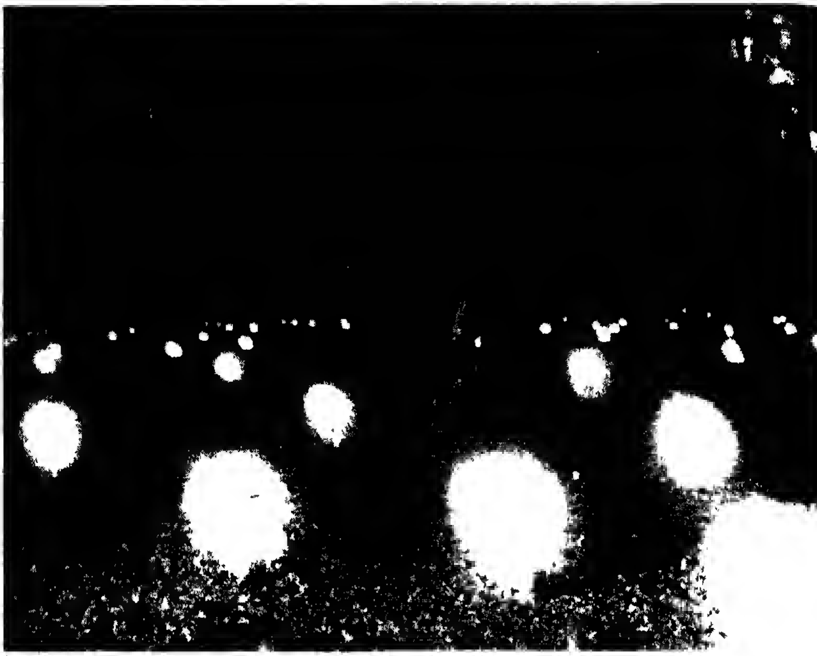


Fig. 87. Heaters in orange grove to prevent damage by low temperatures (U S. Weather Bureau photo)

climate is required to support forests. Rainfall makes the forests. The forests do not cause the rains, though extensive forests do affect the climate to a considerable degree, and may be responsible for a share of the rainfall. To what extent can man control the climate, and especially the rainfall by tree-planting, impounding water to produce lakes and reservoirs, and by other similar means?

The small amount of moisture evaporated from reservoirs and small lakes is carried away in the general circulation of the atmosphere. There is no reason to believe that it would have an appreciable effect on the rainfall in the immediate vicinity. For the United States as a whole or for North America, the rain-producing effect of this additional bit of moisture in the atmosphere might be in the ratio of the size of the lake or reservoir to the Atlantic Ocean including the Gulf of Mexico and Caribbean Sea. Inland bodies of water, such as the Great Lakes, have an influence on

the rainfall roughly in proportion to their size. On the whole it is not large.

Agriculture is not affected by rainfall alone. Lakes, rivers, and accumulations of snow and ice in the mountains provide water for irrigation. Plantings of trees in shelterbelts control the local climate in several ways. When placed at right angles to the prevailing winds the trees protect the land to a distance of ten to twenty times their height, or even more. Snow is not blown so much and some is retained on the ground in the sheltered areas instead of drifting onto highways and into ditches. Evaporation is diminished; the temperature is lowered in the warmer part of the year; and soil blowing is reduced. Protection is afforded to farmhouses and animals during windy weather in winter. In these and various other ways, including strip cropping and rip-rapped dams (Figs. 88, 89, 90), agriculture can be made to succeed on rainfall that might otherwise be inadequate.

On the other hand, the destruction of forests can have very

FIG. 88. Future barriers against the wind. A field shelterbelt in North Dakota. (Soil Conservation Service photo ND-140)

serious consequences. Probably the worst immediate result is the increased rate of runoff of heavy rains and the resultant floods, especially flash floods in headwater streams formerly protected by forest cover.

If all the vegetative cover were removed from the United States, there would undoubtedly be a remarkable change of climate. In the next spring season the temperature over the vast area would rise at a rate unknown in the past. A strong temperature contrast would quickly come into being between the land and the Pacific. The change of wind circulation would be disastrous for further growth of vegetation over large areas "Hot winds of the plains" would dominate the weather in the interior, and the moist winds of the Atlantic and Gulf would be turned to the north and northeast with deficient precipitation even in eastern areas. Hot sun and cool water would produce spring droughts even in coastal areas. Rains would come, often in larger quantities, in the cooler months. Floods would become more frequent and disastrous in autumn and winter. In general, our climate seems to have tended in this direction in the last half century.

Fig. 89. Strip cropping of sudan and cotton in Texas retains water and protects the soil from wind. (Soil Conservation Service photo. Tex-17602)

Fig. 90. Partially filled rip-rapped dam in Oklahoma. (Soil Conservation Service photo. Okla-5026)

Our climate has changed greatly as a result of clearing the land for crop farming, highways, pasturage, and other purposes. As long as we did not fully understand the causes of drought, we discounted prophecies of deteriorating climate. But now that we know how widespread and persistent is the control of the Pacific Ocean in relation to the rainfall of the continent as a whole, we can see that any tendency toward an increase in the temperature contrast between continent and ocean in the spring and early summer months will deprive us of rainfall at the very time of year when it is most important to agriculture. This will make it more necessary to impound the flood waters of the cooler months and retain them for use during the more frequent rainless days in the growing season.

Figure 71 shows that for nearly half a century there was a steady downward trend (with oscillations indicating the solar cycle) in the ratio of rainfall in the first half of the year to that in the second half. It was only in the early thirties that this trend was reversed (we hope not just temporarily), but until the late

thirties this reversal did not mean more rain in the first half of the year but rather less rain in the latter half of the year.

Sometimes it seems almost foolish to discuss rainmaking. It might be thought that in time of serious national drought the solution may be found in heating the Pacific Ocean! But it is not quite so hopeless. If we look back over our discussion we see that periods of drought develop with only slight pressure changes amounting to thousandths of an inch. These changes develop slowly, run a definite course, and then subside slowly. In the beginning or at the end of a period of drought, a relatively slight amount of energy applied at the right time and place might cause a rain-producing system to develop, to deviate from its course, or to begin precipitating over a drought area. It might contribute critically needed moisture at the beginning of the drought or break it before it had run its final course to disaster. That such control is possible in the future is open to little question when we study the slight pressure changes which are effective in certain critical areas at certain seasons. (Figs. 43 and 48.)

Man's attempts at rainmaking, none of them successful to date, have been going on for centuries.[35] Dousing holy men with quantities of water has been widely practiced in many countries where droughts are frequent and severe. In some cases nearly all of the people throw water on each other while going through some queer rainmaking ceremony. To break a drought in Australia the Duri resort to magic, a part of which is drawing blood from the wizards and sprinkling it on other men of the tribe. Bird down is then thrown over their bodies so that they will look like clouds.

The frog was considered the god of waters by some primitive peoples, and beating frogs with sticks was supposed to bring rain.

Zulu women bury their children in the ground up to their necks and go away and wail, with the idea that the heavens will be opened up through pity.

It has been claimed in many instances, beginning in ancient times and continuing up to the present, that battles bring rain

[35] Humphreys, W. J., *Rainmaking and Other Weather Vagaries*. Baltimore, 1926.

either through use of high explosives or the noise of battle. Present-day claims are based on the use of high explosives, but even before gunpowder was invented the claims were just as strong that the clash of sword and shield and the shrieks of the wounded brought rain. Some claimed that the vapors arising from the sweat and blood of battle caused rain. Most battles are fought in good weather between rains, so that rain is likely to follow anyway.

Near the beginning of the present century there were several international congresses on hail-shooting. Guns were mounted in areas where hail had done much damage to crops. Blanks were fired in such a way as to hurl a smoke ring toward the storm cloud. This shooting was supposed to prevent hail. The result was that people were killed or injured by explosions and there were almost endless arguments as to whether or not the lack of hail was due to shooting, or hail that came anyway was to be explained by some fault in the shooting technique. There was no real evidence that hail storms were affected in any way, and the practice was abandoned.

In 1891 the Congress of the United States actually appropriated money for experiments in making rain. The amount was $9,000, which is not much more than a professional rainmaker would expect to get from a Chamber of Commerce today for a good heavy shower (if one happened to come at the right time). The experiment authorized by Congress was carried out in Texas by General Dyrenforth who was appointed a "special agent" for the Department of Agriculture. Dynamite and balloons filled with gas were used. A little rain came but the Weather Bureau, on examining its charts, said it would have rained anyway.

One of the schemes tried in the past is to release quantities of hydrogen gas, which is lighter than air. The hydrogen is expected to create a rising current of air and thus bring rain. There is no proof that this method has caused rain and no satisfactory explanation of why it should. There also have been many schemes proposed for use of giant blowing devices to start vertical currents in the atmosphere.

Forest fires and other large fires sometimes cause clouds, and

it has been claimed that showers have fallen from clouds formed in this way. In time of drought the suggestion is frequently made that fires be started to produce rain. This method has not succeeded.

During the drought years of the thirties it was widely believed in this country that radio broadcasting was preventing rain because of the "large amount of electricity put into the atmosphere." Radio broadcasting started in the early twenties and by the middle thirties had expanded into a major industry. Thousands of letters were written to Congress and to government departments urging that radio broadcasting be discontinued for a period of time to see if rain would come. No action was taken. Broadcasting continued to expand, and in the meantime the rains came again.

No doubt the next great drought will bring insistent demands from all sides that atomic energy be used to produce rain. The facts presented in previous chapters seem to indicate that heat generated for the purpose of producing rain should be applied in such a way that small but critical effects of the Pacific Ocean in late winter and early spring on air flow over the mountains would be counteracted.

Applying heat to raise the temperature of cold ocean currents or using some device to deflect them to other regions is sometimes suggested as a means of controlling climate. There are many other possibilities, if the imagination is given free rein, but if any such plans are feasible it will be necessary to consider all the consequences. The temperature or the rainfall might be made more favorable in a given area, but some adjoining or even distant areas might be adversely affected in a serious manner.

The rainmaker has his own trade secrets. (Fig. 91.) There was one, with the title of "professor," who was exceptionally successful. He had as partners an ex-prize-fighter and a disbarred lawyer. If he failed to collect for his rainmaking he would threaten legal proceedings, and if that failed he would have the ex-prize-fighter use force to intimidate his clients.

Fog has been dissipated successfully, but at a cost which may not be generally justified except in time of war. During World

Fig. 91. "Do you know where I can get some water?" (By permission of "Click," Triangle Publications, Inc.)

War II fog was successfully cleared from airfield runways at bomber bases in England. The invention was called FIDO which meant Fog Investigation Dispersal Operations. It was discovered that if the temperature over an airfield could be raised by 7° Fahrenheit the fog would evaporate. Heat was provided by a line of oil burners on each side of the main runway. Pumps were used to drive the oil to the burners. When there was not too much wind FIDO cleared the fog in ten minutes and in some cases in six minutes. About 6,000 gallons of oil were consumed for each aircraft landed at times when fog had to be cleared.

These facts answer the question, "Can we control the climate?" In a small way we can, and we have made progress. When we buy a home we plant trees in the yard partly to provide shade and thus modify the climate of a small area. We have progressed to the point where we can control summer temperature and humidity in buildings by artificial cooling on a considerable scale. In many other ways we exercise a certain limited control over outdoor climatic conditions, but whether this progress will ever bring us to control of rainfall and weather extremes is undecided. No doubt our cultivation of the land, clearing away of forests, and the building of highways and cities has influenced the amount and distribution of rainfall to a significant degree. In other respects, it is so much easier to travel to a different climate than to try to change the climate at home that large-scale efforts in the future are likely to be limited to production of rainfall, to conservation of the rain which falls, or to causing small temperature changes at critical seasons to avert damage from frost or freezing temperatures. In increasing numbers we travel north in summer and south in winter, and that is a more pleasant and less expensive method of getting the climate we want.

At any rate, when and if we succeed in controlling the climate in more than a local and limited degree, we will need broad and effective regulatory measures to make sure that changes which are advantageous in one area will not be allowed to produce disasters in other areas.

XVIII. IS OUR CLIMATE CHANGING?

In recent years we have been forced by circumstances to change our ideas regarding climate. Fifty years ago, when we were making progress in accumulating weather records in all parts of the United States, we were of the opinion that a good 20-year record could be used as a "normal" and that succeeding 20-year periods would not show any important differences. "Normals" are useful. For example, when we have an unusually cold winter, we need to have some standard for comparison so that we can say that the average temperature was 5° or 10° or some other number of degrees below the normal. Nevertheless, the use of "normals" as measures of fixed climatic conditions has turned out to be misleading. We now have detailed temperature records for more than a century at a number of places in the United States, and we can cite some examples.

The first systematic weather record in North America was begun in 1644 by the Rev. John Campanius near Wilmington, Delaware. It would have been exceedingly fortunate if these observations could have been continued by interested persons in that locality. But nearly a century and a half passed before the beginning of any weather records which are continuous to the present time. Records of temperature at New Haven, Connecticut, began in 1778 and have been continued to the present, but there were breaks in the first two years and there was no record in 8 months of 1795. This makes the record continuous from 1796 to the present day. Temperature records were kept at Charleston, South Carolina, beginning in 1738, but there were some long breaks, and the record is continuous only from 1823 to the present.

There are fewer long records of rainfall than of temperature. The Charleston rainfall records are continuous from 1832, and New Haven only from 1873. New York rainfall records have been kept without interruption from 1826, Boston from 1818, Philadelphia from 1820, Albany and Marietta from 1826, St. Louis and St. Paul from 1837, San Diego and San Francisco from 1850.

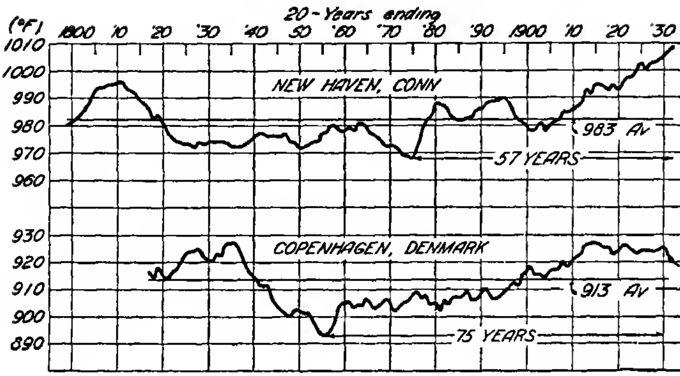


FIG. 92. 20-year moving temperature summations for New Haven, Conn., and Copenhagen, Denmark. (Kincer)

These examples indicate the length of records available for scattered places, the majority being in Atlantic states. The number of records is not adequate for a satisfactory study of climatic changes until after 1870.

Of course, temperature, like rainfall, has variations from year to year. We expect them. But there are long trends which show us that we cannot expect the variations in climate to remain within the limits recorded in a period of twenty or even fifty years. The records for New Haven and Copenhagen are shown in Figure 92. These are 20-year moving temperature summations taken from a study by Kincer. Each year's temperature plot is the sum of temperatures for that year and the preceding 19 years. The scale at the left can be divided by 20 to get average temperatures.

If we had selected the 20 years ending about 1875 to use as the "normal" yearly temperature at New Haven, it would have been 48.5°. In the next half-century there were only eight years at New Haven in which the mean temperature for the year was so low. In 42 years out of 50 the temperature was above the "normal"!

There have been some claims that the building of cities and artificial heating caused these long upward trends in temperature, but there are two answers: (1) There was a very warm period at New Haven in the 20 years ending about 1810 when artificial heat

could not have been the cause, for it became colder again in later years; and (2) records such as those shown in Figure 93 for Philadelphia and nearby West Chester show the same trends. The records at Philadelphia, as analyzed by Kincer, are shown in Figure 94 in annual and in 5-year, 10-year, and 20-year summations.

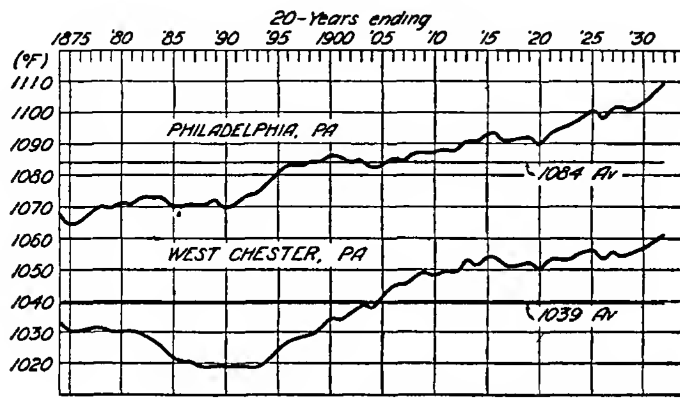


FIG. 93. 20-year moving temperature summations for Philadelphia and West Chester, Pa. (Kincer)

The same trends are found in many other parts of the world as well as in the United States.[36] The recent trend shown by the records of four hundred stations around the world is shown in Figure 95, from one of Kincer's studies.[37]

The cause of these long-time trends is not definitely known. Averages for 20 years smooth out nearly all of the variations, oscillations and sub-oscillations; and the main features which remain are probably the result of some persistent change in solar radiation, in the condition of the atmosphere, the lag of ocean temperatures, or some combination of these.

[36] Matthes (1945) cites the observations of Broggi as unmistakable in their indications that the present glacier recession, which began in South America about 1862, has proceeded simultaneously with the recession in the Northern Hemisphere (Europe and North America).

[37] Kincer, J. B., "Relation of Recent Glacier Recessions to Prevailing Temperatures." *Monthly Weather Review*. June 1940.

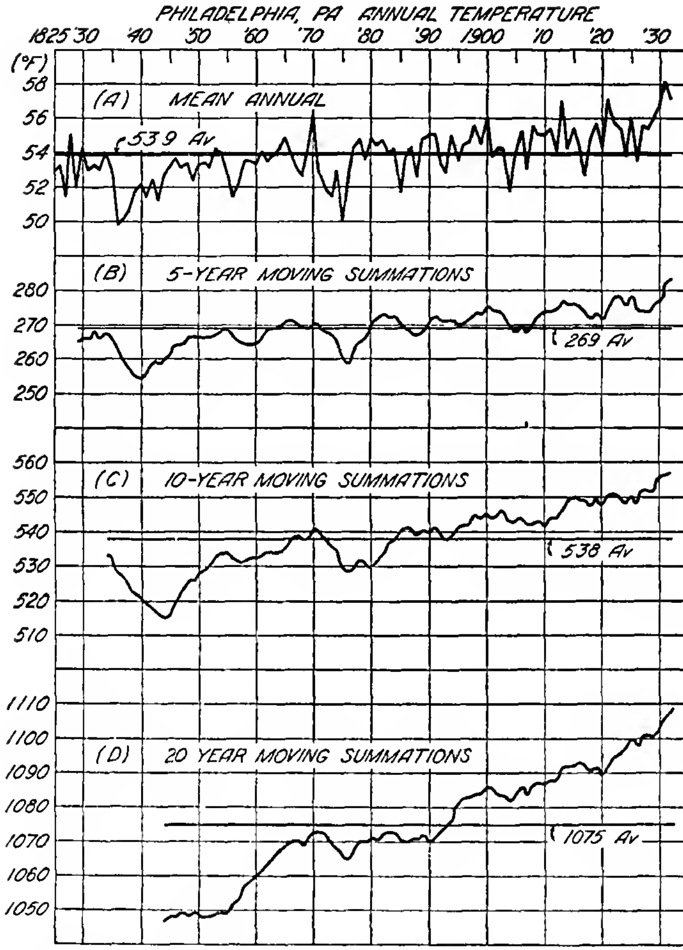


FIG. 94. Mean annual temperature at Philadelphia. (A) Unsmoothed; (B) 5-year moving summations; (C) 10-year moving summations; (D) 20-year moving summations. (Kincer)

Humphreys has called attention to the effects of volcanic dust in the atmosphere. He has shown that world temperatures have been lower at and after times of great volcanic eruptions The famous "year without a summer" (1816) followed the great erup-

tion of Mt. Tamboro (Dutch East Indies) which killed 56,000 people and threw so much dust into the air that it was dark for three days at a distance of three hundred miles. The eruption of Krakatoa in 1883 threw great quantities of dust into the atmosphere. It was followed by cold years and the upward trend of temperature in later years may have been due in a small measure to a slow recovery as the dust was dissipated. However, the upward trend at New Haven and Copenhagen (Fig. 92) definitely began before the Krakatoa eruption.

There have also been some long trends in rainfall. The recent upward trend in temperature in the United States was accompanied by a downward trend in rainfall. One of Kincer's diagrams (Fig. 96) shows these trends.

The most likely cause of trends is long-term variations in solar

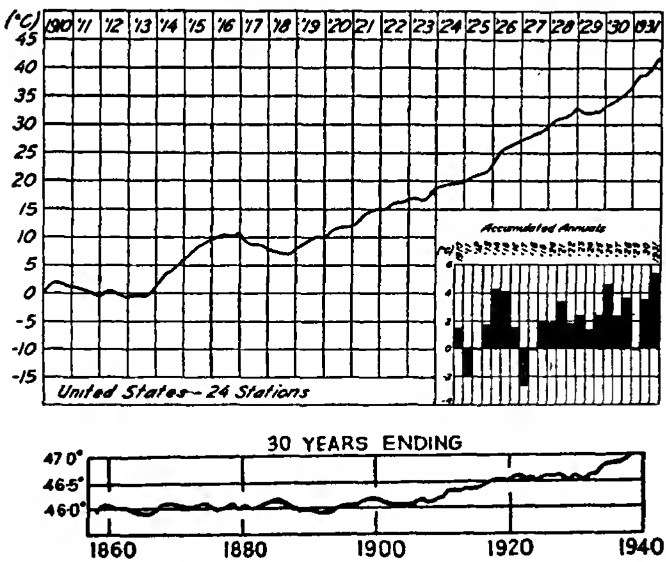


FIG. 95. Upper curve, accumulated monthly departure from normal temperature, 1910 to 1931, as an average for approximately 400 places around the world (10,000 monthly records) for 22 years, showing general upward trend. Small inset, accumulated annual departure, same places. Lower curve, march of temperature at selected places in West Europe, 1830 to 1938. (Kincer)

radiation, but we do not have data to check this. Accurate measurements of solar radiation received in the earth's atmosphere are difficult. The Smithsonian Institution has done most of the work in this field. The records are too short for use in a discussion of trends. There is the added difficulty that the work has not long been out of the experimental stage. The condition of the atmosphere affects the radiation which reaches the earth's surface even at high elevations in regions where the atmosphere is very clear. New corrections have been applied, and revised methods have been adopted from time to time. Eventually a long record by standard methods will provide a body of data of the highest importance. The maintenance of the observations must rest on the potential value of data accumulated in the future as well as on their practical usefulness in studying present-day weather changes.

Variations in solar radiation and their effects on ocean temperatures are of great importance. It seems obvious that heat stored in the oceans during periods of high solar activity will not be completely dissipated for years, even with diminished solar radiation. Brooks has calculated that if the earth's surface were entirely water and if solar radiation were increased above "normal" enough to raise the temperature of the oceans by 18°, the heat stored in the oceans would be enough to keep the temperature 3.6° above "normal" for 250 years under average sunlight.

The preceding discussion shows how little we know about the causes of trends. One fact is important. Trends are world-wide, and in similar locations the trends seem to be the same. Clayton and others have shown how these trends are related in different parts of the world. Clayton ascribes them to variations in solar radiation, and this seems to be the only acceptable explanation.

Claims of changing climate are frequently heard. The traveller is accustomed to hear natives say that "we never had weather like this before." We often hear the remark that the weather is not the same as it was when "grandfather was a boy." As accurate instrumental records accumulate we begin to see the truth in these statements. We may hope that some future generation will say that the weather is not so hot and dry as it was when "grandfather was a boy" (in the years from 1930 to 1939).

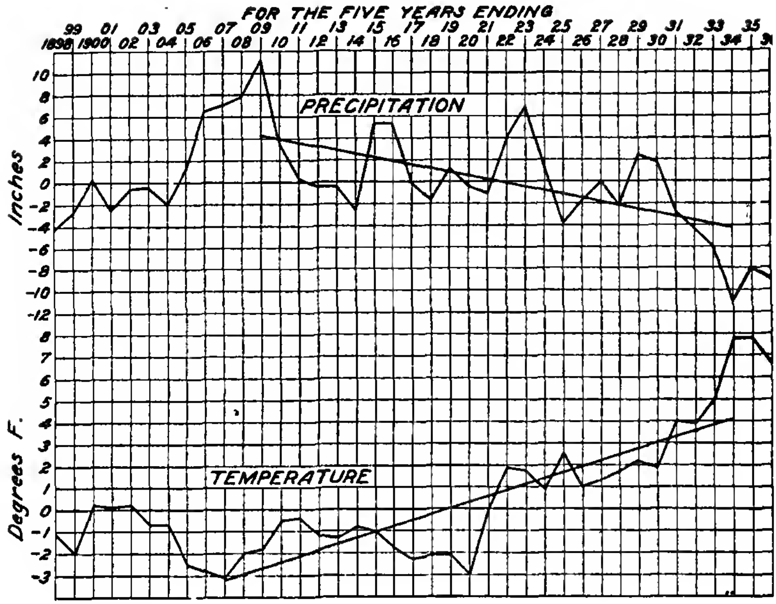


Figure No. 17.

FIG. 96. Progressive five-year sums of temperature and precipitation departures from normal for the United States. (Kincer)

In 1804 a Frenchman named Volney published a book[88] on the climate and soil of the United States. He quoted Thomas Jefferson and others to show that the climate was changing. Jefferson wrote that the snows were less frequent and not so deep. No doubt there were some long-term trends in climate in the years during and preceding Jefferson's time.

There are also seasonal trends which are of great importance. The temperature and the amount of rainfall in the growing season, as well as the length of the growing season, are of much concern. We have seen (Fig. 71) the trend toward less rain in the first half of the year as compared with the second half, and also (Fig. 83) the oscillations and trends in Bismarck temperatures.

[88] Volney, C. F., *View of the Climate and Soil of the United States of America*. London, 1804.

At Bismarck the upward trend in annual temperature has been attended by a remarkable shift in temperature between early and late winter. Near the beginning of this trend (Fig. 97) February at Bismarck averaged 14 degrees *colder* than December in the three years 1889, 1890, and 1891, while in 1925, 1926, and 1927, near the top of the trend, February averaged 10½° *warmer* than

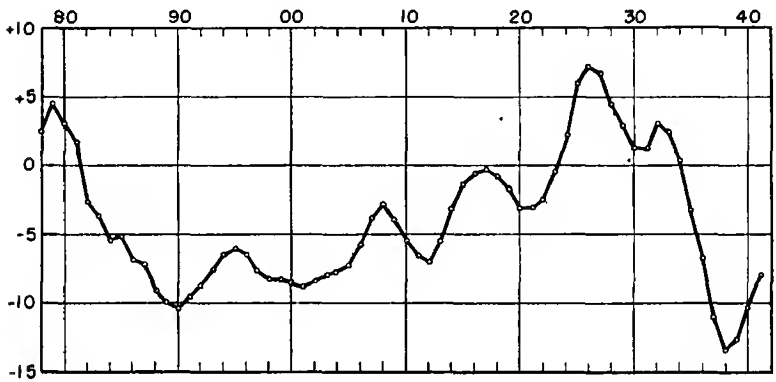


FIG. 97. Differences of temperature between February and December at Bismarck, N.D. Scale in whole degrees (F.) shows excess or deficiency of February as compared with December. Smoothed by formula given under Figure 71.

December. This makes a total difference of 24½° in mean monthly temperatures in winter at Bismarck. This change affected the entire country. The differences are charted for a few selected places in Figure 98. It is apparent that this trend was due to a progressive change in the timing of the flow of cold surface air from Canada into the United States.

In December the oceans are relatively warm but continue to become cooler until February or March. In February the continent is already growing warmer in the south, but the polar regions continue cold. The result is that there are two surges of winter in the United States. The first is dominated by overflow of warm Pacific air into the Canadian sink as the temperature falls in autumn and early winter. Cold surface air drainage from Canada into the United States keeps the temperature down. As the sun

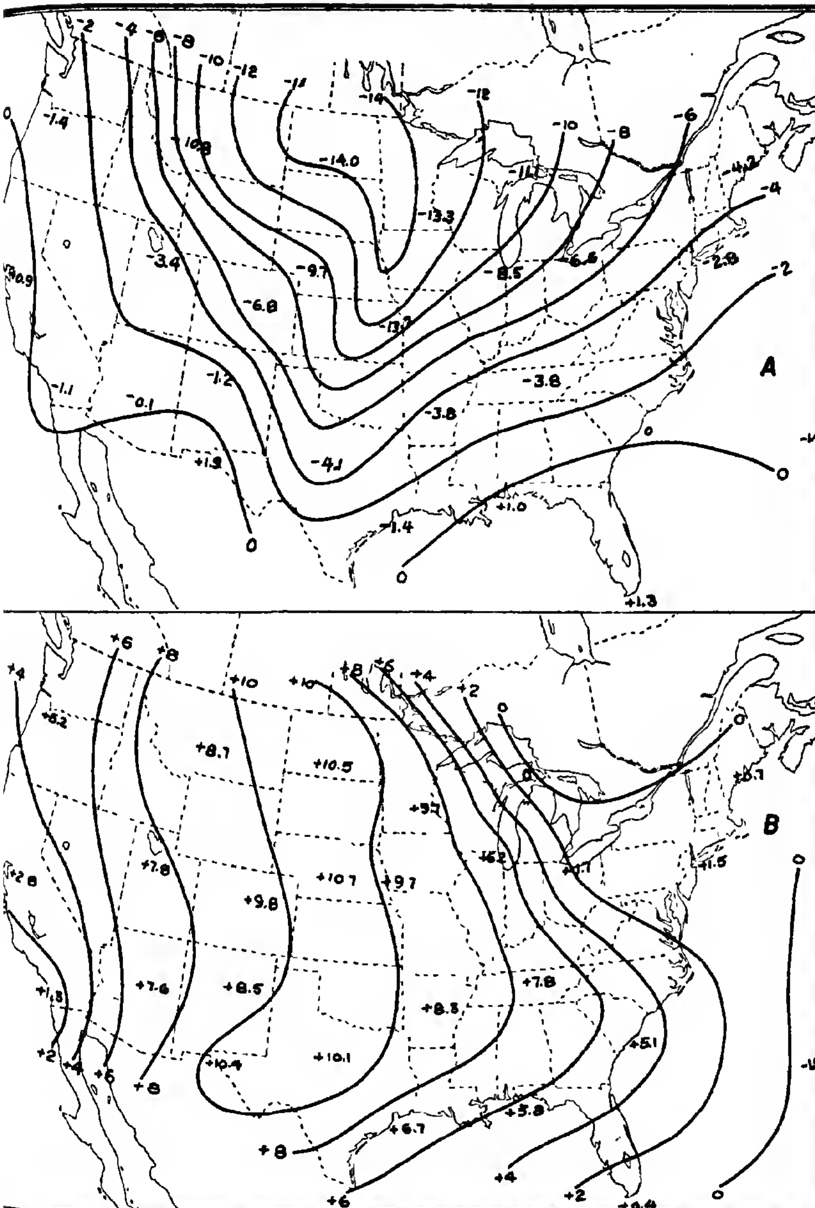


FIG. 98. Excess or deficiency of February temperatures compared with December temperatures. A. Average for years 1889, 1890, and 1891. B. Average for years 1925, 1926, and 1927. See Figure 97.

comes northward in February the temperature contrast between the equatorial and polar regions increases in the Northern Hemisphere and cold outbreaks from the far north to a large extent replace the Pacific overflow in lower latitudes as the Pacific becomes *relatively* cooler.

It is apparent that these two surges of winter are similar to the two sub-oscillations in the sunspot cycle. There is an interval which is known as the "January Thaw" between the surges of winter, just as a warm and droughty period is likely to occur between the two sub-oscillations in the solar cycle.

On this basis the trend at Bismarck presumably represents the effects of rising solar radiation. The colder Decembers show an increase in the cold surface air stream flowing from Canada to the United States. The fact that it is primarily a surface phenomenon due to horizontal motion of the surface air is shown by Figure 99 which gives the differences in mean temperatures each year

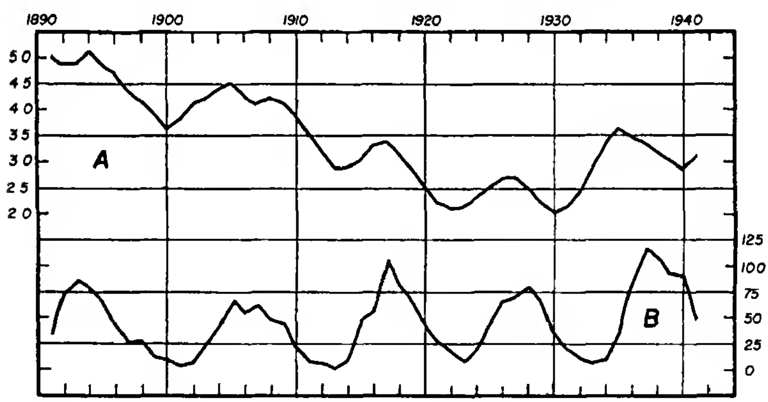


FIG. 99. A. Mean annual temperature differences between Cheyenne (6,088 feet) and Bismarck (1,674 feet) in degrees and tenths (F.) by scale at left, which shows Cheyenne warmer than Bismarck by amounts ranging from 2° to 5°. Cheyenne is at a much higher elevation and, except for effect of cold surface air drainage from Canada, would be colder than Bismarck. B. Sunspot numbers by scale at right. Note that Bismarck became relatively colder (Cheyenne warmer) near each sunspot maximum. See also Figures 75 and 98, which indicate the shallowness of the cold air stream causing these pronounced temperature changes in North Dakota and elsewhere in the region to the east and south.

between Bismarck (1,674 feet) and Cheyenne, Wyoming (6,088 feet). Bismarck was colder compared to Cheyenne in the late eighties, and it became relatively colder with each rise of solar activity in succeeding sunspot cycles as the cold surface airstream increased temporarily. But in the trend the average temperature at Bismarck was progressively rising toward that at Cheyenne. Bismarck was about 5° colder than Cheyenne in the early nineties and only about 2° colder in the early twenties and early thirties. Late in the thirties Bismarck became relatively colder again, evidently due to great solar activity near the time of the great sunspot maximum in 1937 and 1938.

In the same period that the February cold at Bismarck was diminishing, the December cold caused by Pacific overflow was increasing. During this time the rainfall in the United States was shifting to the latter part of the year, and the first half of the year was becoming increasingly dry (Fig. 71). This change in rainfall distribution corresponded to the prevalence of cold air masses arriving from Canada. It is apparent that the cold air from Canada was not very deep, and Bismarck was affected more than Cheyenne.

These trends are accompanied by important seasonal changes in climate. The shift of rainfall in latitude shown by differences in rainfall between Wisconsin and Louisiana (Fig. 86) is an example. Trends may appear slight when shown in yearly values, but they are composites of seasonal changes of different character, and the changes in the seasons may be of the greatest importance.

Prevailing winds from the west in our latitude carry the weather from the Pacific to our western shores and the weather of the continent toward the east and to the Atlantic. Therefore, the weather of our west coast is widely different from the weather of the eastern shores even though both are on large bodies of water. If there were no prevailing westerlies the climate of the two coasts would be much the same. Following through this reasoning, we know that the stronger the circulation of the atmosphere becomes, the greater will be the contrast between the eastern and western coasts of the United States. This is especially noticeable in winter. With strong circulation of the atmosphere, Pacific winds of mod-

erate temperatures dominate the weather of the west coast while the cold extremes of the interior of the continent are carried to New England and the middle Atlantic coast, sometimes extending as far down as the Carolinas and Florida. For example, Charleston, South Carolina, and San Diego, California, are in the same latitude; Charleston averages nearly 15° warmer than San Diego in summer and nearly 5° colder in winter. This occurs even though the warm Gulf Stream lies to the east of Charleston and the cool

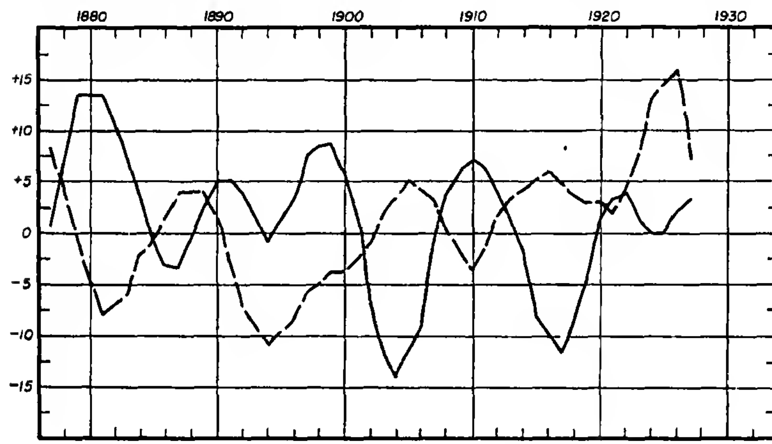


FIG. 100. Solid line, sum of smoothed annual temperature departures from normal at Eastport (Me.) and Charleston (S.C.). Dashed line, same for Portland (Ore.) and San Diego (Calif.). Scale at left shows tenths of degrees. (See smoothing formula under Figure 71.)

California Current flows to the west of San Diego. In general, in years when San Diego is warmer, Charleston is cooler, and vice versa. Farther north, Portland, Oregon, and Eastport, Maine, show the same effects, but in a more violent and irregular manner because of the stronger circulation of the atmosphere in higher latitudes. Figure 100 shows annual temperature departures averaged for Eastport and Charleston (solid line) and for Portland and San Diego (dashed line). When the temperature curve at Portland and San Diego goes upward, it is likely to go downward at Eastport and Charleston, and vice versa. But because of the

slower response of the Pacific Ocean, changes in the Pacific coast temperatures appear to be somewhat delayed.

The northern group of states is affected more by invasions of cold air from the north than the southern states. Figure 101 is a smoothed curve showing the temperature differences between three representative northern places combined (Portland, Bismarck and Eastport) and three representative southern places combined (San Diego, Galveston and Charleston). The oscillations in the sunspot cycle and the upward trend are the outstanding features of this curve. The data have been smoothed so that short-period variations and sub-oscillations are almost entirely removed.

Changes of climate, as we know them from instrumental records, represent changes in the circulation of the atmosphere caused by variations in the temperature contrasts between equator and poles and between continent and oceans. The changes are

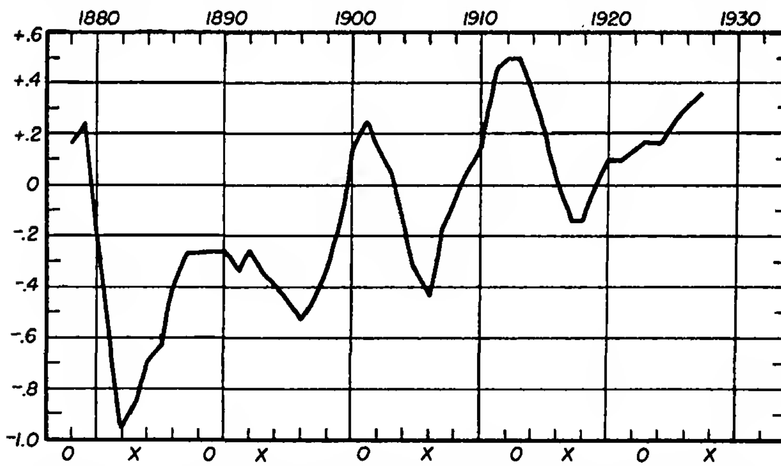


FIG. 101. Smoothed differences in annual temperatures averaged for three northern cities (Portland, Ore., Bismarck, N.D., and Eastport, Me.) and three southern cities (San Diego, Calif., Galveston, Tex., and Charleston, S.C.). Scale at left shows differences in departures from normal in tenths of degrees (F.). Positive values show that the northern stations were relatively warmer; negative values, colder. At the bottom of the diagram X's show time of maximum sunspots; O's, minimum sunspots. (Smoothing formula given under Figure 71.)

therefore different in different parts of the country. We conclude that when solar radiation is increasing or decreasing either in the sunspot cycle or in other longer cycles or trends, the changes of weather or climate are most pronounced. The more rapid the change in solar radiation that goes on for any considerable time, the more profound will be the temporary changes in climate, but as soon as solar radiation ceases to rise or ceases to fall in the long-term trend, the climate tends to come back to approximately its "normal" pattern. By "normal" we mean the average climate over a very long period, perhaps a thousand years or more. But "normal climate" is hard to define. If the average for a thousand years is taken, the "normal" climate will be found to have changed through the ages. The rocks tell us of cycles of climatic change, and the recurrent pattern is one of the greatest puzzles of geological history. This question will be discussed briefly in the next chapter.

XIX. DROUGHTS THROUGH THE AGES

It is usually not wise for a meteorologist to write about geology, but the accurate records of the weather are so short and the records of the rocks are so many millions of years long (Fig. 102) that we are tempted to use what we know from our brief climatic records to help explain what has happened in past ages, with the hope that the records of the past may help us to a better understanding of what may happen in the future. A brief review of the outstanding facts will be appropriate.

Throughout the period of geologic record the earth's crust has had about the same temperature as today. Therefore it appears that very little climatic change, if any, can be ascribed to heat from within the earth.

In early geologic times there were important changes in the distribution of land and water, and certainly there were periods of upheaval and mountain building. These changes must have had widespread effects on the climate.

Within historical times there has been no change of consequence in the distribution of land and sea, or in the height of mountains. But there may have been changes in the amount of ice in polar regions, and there is historical evidence of some changes in glaciation elsewhere.

Geologists have brought forth records to show without any question that in the relatively brief time man has existed on the earth there has been no period of years with what might be called "normal" climate. For millions of years the climate of the earth was much milder and more uniform than it has been in recent centuries. One of the many explanations is that the earth received more heat from the sun during long ages in the past. But that does not mean that our present cold climate is caused by a permanent decrease in heat from the sun, for the evidence of geology is that glacial periods have occurred several times in the history of the earth, and these other cold periods were followed by long spells of warm climate lasting for millions of years before another ice

age came along. It is reasonable to assume that in the future there will be other periods of warm climate on the earth.

Examination of climatic changes in recent centuries reveals that greater heat from the sun is not the only requirement for a genial and uniform climate. We believe that increased solar radiation or rapid change in solar radiation causes a more vigorous circulation of the atmosphere and tends to accentuate the extremes of weather. The increased solar radiation which comes with more sunspots is attended temporarily by more storminess. Huntington, Kullmer, Bigelow, and others have found that storm tracks change with sunspots and that storminess is generally greatest in the United States at times of sunspot maximum.

It has been difficult to explain why, in the warm periods of geological history, it was much warmer in the regions near the poles than at present. During these periods more extensive deserts or at least semi-arid conditions seem to have prevailed over the continents. There is evidence that dry conditions expanded during the times of warm climate, and this agrees with our experience that warm weather and dry weather go together. But the warmth of the polar regions in prehistoric times has been a mystery.

Many explanations have been offered for these recurrent periods of warm droughty conditions of climate and the shorter intervals of glacial climate. Most geologists agree that at intervals widely separated in time there have been vast upheavals which produced mountains. The mountains were worn away again very slowly. Great climatic changes were associated with mountain building. We know also that the seas have expanded at various times, and probably all parts of all the continents have been flooded at one time or another. Such events would cause great changes in climate. But even with the oceans covering all of the earth, if it continued to revolve around the sun with its axis tilted so that the polar regions were alternately turned toward and away from the sun, it seems that there should be pronounced changes in temperature between winter and summer in higher latitudes.

Several explanations have been offered for these remarkable changes in climate. Briefly, these explanations include (1) slight changes in the inclination of the earth's axis and the so-called

ERA	PERIOD	EPOCH	ROUGH PROPORTION OF GEOLOGICAL TIME (PERCENT)	NOTES	WORLD-WIDE REVOLUTIONS
ARCHEAN (ARCHEOZOIC)			32+	GEOLOGICAL EVENTS INDEFINITE	
ALGONKIAN (PROTEROZOIC)			32-	A FEW TRACES OF LIFE	
PALEOZOIC	CAMBRIAN		7-	ABUNDANT LIFE IN THE SEAS	
	ORDOVICIAN		4	OLDEST KNOWN FISHES	
	SILURIAN		2-	OLDEST LAND PLANTS AND ANIMALS	
	DEVONIAN		3-	AMPHIBIANS AND FORESTS ON LAND	
	MISSISSIPPIAN (CARBONIFEROUS)		2-	AMPHIBIANS DOMINANT ON LAND	
	PENNSYLVANIAN (CARBONIFEROUS)		3	EARLY REPTILES ON LAND	
	PERMIAN		3-	EXTINCTION OF MUCH PALEOZOIC LIFE	
MESOZOIC	TRIASSIC		2-	PRIMITIVE MAMMALS ON LAND	
	JURASSIC		2-	REPTILES DOMINANT, FIRST BIRDS	
	LOWER CRETACEOUS (COMANCHEAN)		1+	SPREAD OF MODERN INSECTS AND PLANTS	
	UPPER CRETACEOUS		3-	EXTINCTION OF LARGE REPTILES	
CENOZOIC	TERTIARY	PALEOCENE	2+	RAPID SPREAD OF MAMMALS	
		EOCENE		MODERN MAMMALS, GRASSES, AND FRUITS	
		OLIGOCENE		RISE OF ANTHROPOIDS	
		MIOCENE	2-	"GOLDEN AGE" OF MAMMALS	
		(PLIOCENE?)			
	QUATERNARY	PLEISTOCENE		MAN APPEARS, EXTINCTION OF MANY MAMMALS	
		RECENT		DOMINANCE OF MAN	

FIG. 102. A geological time scale. Each figure in the central column represents roughly about ten million years. (From *Climate and Man.*)

precession of the equinoxes; (2) long-term variations in solar activity; (3) close approach of another star to our sun and the consequences, which might be sufficiently catastrophic to explain any climatic change; (4) variations in the amount of carbon dioxide or ozone in the atmosphere; (5) great variations in the amount of volcanic dust in the atmosphere; (6) drifting of the continents toward or away from the equator; (7) crustal unrest and mountain building; (8) changes in the amount of ice in polar regions; and (9) escape of heat generated by radioactive substances. Some of these are problems for the astronomer and the geologist. Long-term variations in solar activity, the amount of dust in the atmosphere, and polar ice are more acceptable to meteorologists as explanations of climatic changes in the light of climatic conditions of our times.

Brooks[39] has offered an explanation which seems to be in accord with our knowledge of climatic changes in recent centuries. He has shown that the nature of the earth and its atmosphere, the freezing point of water, the temperature of the maximum density of water, and the cooling effects of large ice sheets are such that the earth's climatic pattern is rather critically balanced, and that a relatively small change in the heat received at the earth's surface eventually causes the growth or dissipation of polar ice sheets which in turn have a marked effect on the circulation of the atmosphere and the distribution of temperature. (Fig. 103.) Brooks shows that a relatively small lowering of average temperature from that of the warm periods would cause ice to begin to form in polar regions. The ice might persist through one summer season and grow further in the next winter. An ice sheet acts like snow-covered land in high latitudes. It loses its heat rapidly by outward radiation and will grow more and more rapidly with increasing size. The whole train of circumstances favorable to ice accumulation which comes into play seems to be almost sufficient to account for widespread glaciation. Volcanic dust and other circumstances may contribute to the final result.

Extensive ice in the polar regions certainly causes an increase in cold surface winds from the polar regions toward the equator and

[39] Brooks, C. E. P., *Climate through the Ages.* London, 1926.

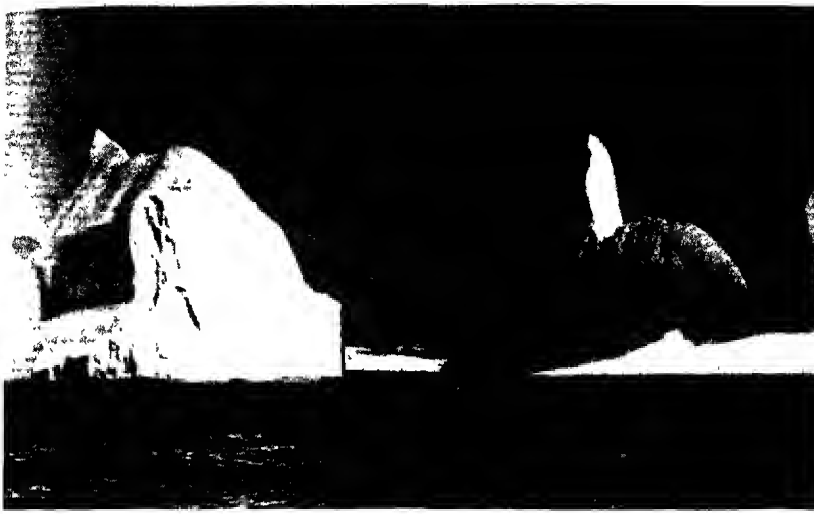


Fig. 103. Products of polar ice sheets. Icebergs in the North Atlantic. (U.S. Coast Guard photo)

tends to keep the surface air temperature down in high latitudes of the Northern Hemisphere and to a lesser degree in high latitudes of the Southern Hemisphere. On the other hand, the disappearance of ice in the polar regions would certainly bring a milder climate.

Brooks believes that during times when there was no polar ice sheet and the polar regions were much warmer, the sub-tropical highs over the ocean were more expanded than at present. For example, he thinks that the Pacific high as it now exists in July (Fig. 34) would be representative of the situation during the whole of the year in warm periods. Certainly a migration of continental heat to the northward would cause the Pacific high to expand northward.

A higher temperature over the continental areas in the far north would surely reduce the amount of overflow from the Pacific into the Canadian "sink," and north-to-south motion of surface air into the United States would also diminish. Warmer polar regions would contribute less than at present to cold air invasions into middle latitudes.

Another thought offered by Brooks is that the circulation of the

atmosphere which in recent centuries includes a system of outflowing easterly winds from the polar regions (Fig. 68) is part of a critically balanced system, and that in the absence of a polar ice sheet there would be weak polar east winds, or none at all. The westerlies would then carry warm surface air into high latitudes. This would add to the warmth of the polar regions during winter time.

Humphreys[40] and others have offered an explanation of climatic changes which is essentially classical.[41] They believe that great changes in solar radiation in past ages are not demonstrated and in fact are not required as an explanation of geologic changes of climate. For the most part, Humphreys relies on volcanic activity and dust in the atmosphere to explain the observed depressions of temperature on the earth. He employs a combination of sunspot numbers and variations in temperature presumably caused by volcanic dust. This widely accepted hypothesis attributes most of these changes to terrestrial causes, but depends on sunspots as a minor factor in explaining some of the temperature variations which obviously cannot be attributed to dust in the earth's atmosphere (Fig. 104).

Humphreys lays stress on the well known fact that periods of glaciation and mountain building were more or less coincident, and points out that it is more reasonable to assume that mountain building, variations in continental levels, and great volcanic activity went together rather than to assume that crustal unrest and mountain building accidentally coincided with great solar variations. In the United States it is advisable to consider also the role of mountains in translating solar variations into weather changes in the lowest level of the earth's atmosphere. The following discussion is appropriate to this treatment of drought, because great changes in the amount and distribution of precipitation were obviously connected with widespread glaciation.

It is not necessary to assume that solar changes *just happened* to coincide with mountain building, unless we take the view that

[40] Humphreys, W. J., *Physics of the Air.* New York, 1939. Contains a full discussion of the volcanic dust hypothesis.

[41] The term "classical" is explained in the introduction.

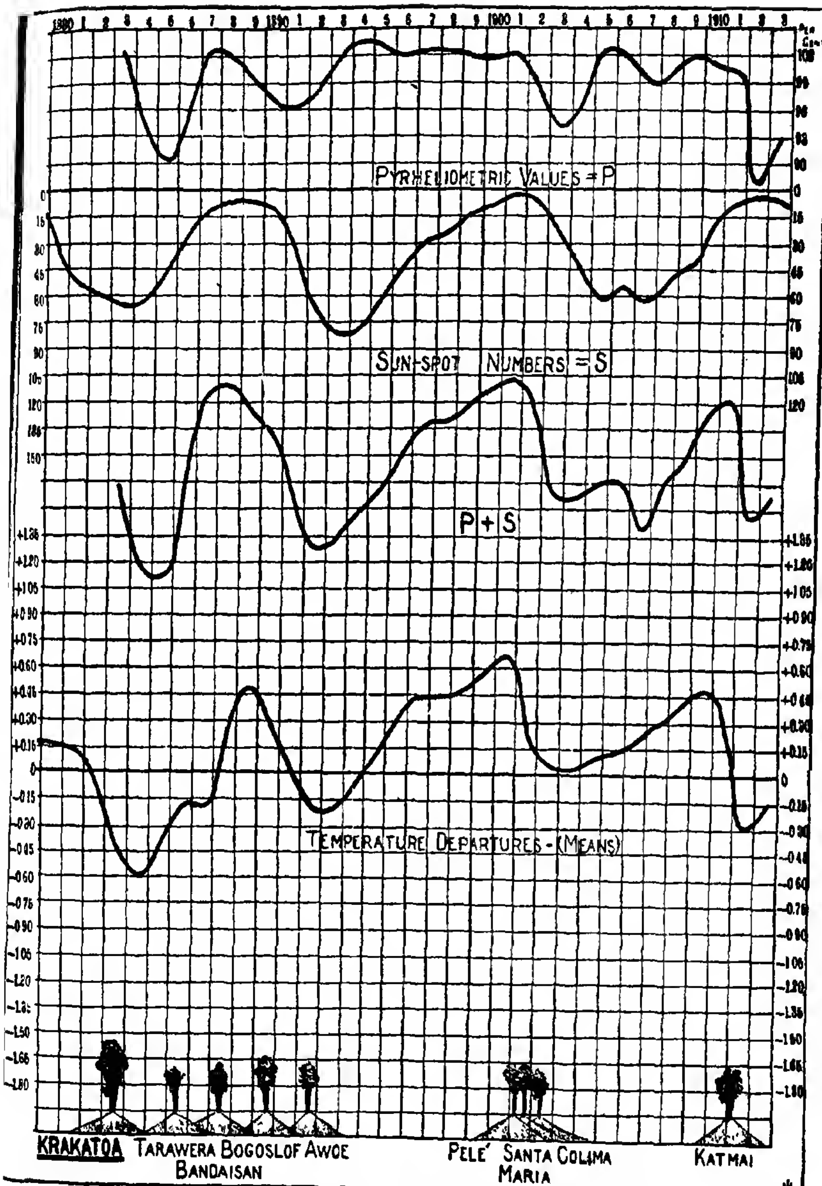


Fig. 104. Relation of pyrheliometric values (solar radiation measurements) and mean temperature departures to sunspot numbers and volcanic eruptions. (Humphreys in *Bulletin of Mt. Weather Observatory*)

the solar changes we have observed in the last seventy years are inadequate to account for the climatic changes of geologic times. We must assume that the solar changes we have observed in recent centuries have been occurring for millions of years. This assumption is more reasonable than the view that solar changes as indicated by sunspots are peculiar to recent times.

We have seen the influence of the Rocky Mountains in relation to Pacific temperatures in causing the flow of air in some years to go over the mountains in the north and bring cold air masses and rain and snow to the United States and in other years to go over the mountains in the south and bring warm dry weather to the United States. These changes in the flow of air over the mountains are geared to solar variations as evidenced by sunspot numbers. (Fig. 86.) If we removed the mountains, the air would flow freely across the United States from the Pacific, and the north-south oscillations and trends would diminish or cease. The northern part of the United States east of the Rockies would cease to be the scene of our great conflict of cold and warm air masses. This region is precisely the region where glaciation has staged some of its advances and retreats of geologic times.

We need only to assume what Brooks has postulated, on the most reasonable climatic evidence available, that polar ice began to accumulate because of temperature changes that are within the range of probability as indicated by what we have actually observed. (Fig. 98.) From this point we have a chain of circumstances which fits with what is now going on. The growth of polar ice intensifies the Canadian sink east of the mountains. Cloudiness, rain, and snow become more frequent in the United States. At each time of maximum sunspots the belt of maximum precipitation moves northward to the edge of the ice sheet and heavy snowfall adds rapidly to the accumulation. The cold sub-oscillation follows quickly and the accumulation fails to melt. The intermediate warm and dry periods between the sub-oscillations become brief or non-existent. It is easier to account for glaciation than it is to explain how to get rid of the ice after it has accumulated. In the absence of mountains, these same solar changes would have an entirely different effect.

It is not necessary to have recourse to the precession of the equinoxes, the amount of ozone and carbon dioxide in the atmosphere or the eruption of volcanoes to account for climatic changes. These occurrences may have had some effect, but basically all we need is an explanation of climatic changes going on now. This explanation will take care of the period since our existing mountains were built, and it will point to the probabilities of the future.

Whether changes in solar radiation alone caused the ice to melt or other causes worked in conjunction with solar changes is immaterial from the standpoint of rainfall and drought. In either case the fact remains that relative warmth of the polar regions would contribute to a deficiency of rainfall in the United States. Assuming that a considerable part of extreme northern Canada would be submerged in warm periods, winter cold of the continent would be much less severe and would be centered farther south, where it would be less effective in producing rain. The Pacific overflow into the continental sink would be weak and would take place in lower latitudes. The dry winter climate of the northern plains would spread over much of the interior of the United States west of the Ohio and lower Mississippi Rivers. The expansion of the Pacific high would cause chronic droughts in summer over practically the entire country.

In the absence of mountains, regardless of polar ice, most of the United States would get its rainfall directly from the Pacific, and the region of summer drought would spread far to the eastward. Our Gulf States probably would have wet winters and dry summers, like the Mediterranean countries.

These conclusions are especially interesting in relation to changes which have occurred in historic times. There have been wide swings from dry and warm to cold and wet conditions in Europe in the last 2,000 years. During the tenth and eleventh centuries, for example, the climate was very dry and warm in Europe. There are indications that the arctic ice cap may have disappeared entirely. European explorers were able to take routes of travel that they would find impossible now because of ice.

Greenland was settled in A.D. 984. The settlers brought cattle and sheep which survived for a considerable time. These colonies

disappeared during the fifteenth century. Recent excavations have shown that at first the soil permitted bodies to be buried to a considerable depth. Subsequent graves were shallower. At present the soil is frozen solid all year long. This evidence shows that Greenland was much warmer in the tenth century than at present, and there was much less ice or perhaps none at all, at least for a short period of years.

Whether or not this period of warmth and drought in Europe and mild climate in Greenland was experienced also in North America is not clear. Evidence of tree-rings does not support this conclusion. But the long tree-ring records apply mostly to southwestern and western United States. In recent years rainfall as measured by gages shows wide swings from one part of the country to another. There is no reason to believe that the rainfall of California or Arizona is a key to the rainfall of the entire country during such a trend.

Another example of climatic change is found in Yucatan. Huntington investigated the ancient Maya civilization. He showed that at one time Yucatan was inhabited by a prosperous race which scarcely could have existed in such a civilized state in the hot moist climate which has prevailed there in recent times. There was a long period of active development which culminated in the building of great cities in the southern areas of Yucatan This civilization lasted from about A.D. 100 to A.D. 350, after which there was a rapid decline. There was a revival about A.D. 900 to A.D. 1000, farther north in Yucatan, lasting one or two centuries. Huntington believes that these periods of great activity must have developed in drier and more stimulating climatic conditions than exist there at present. On the other hand, erosion, leaching, and encroachment by weeds are thought by some writers to be the primary factors in the decline of the Maya civilization. But these effects could have been associated with increasing rainfall.

Huntington has also furnished evidence from the history of the ancient people of southern Arizona that there have been important changes of rainfall in that region in past centuries. Other examples could be mentioned, but a lengthy discussion of this topic is not appropriate in a study of drought.

Enough instrumental records have now accumulated so that we can show quite definitely that there have been long-period and persistent changes of the kind discussed by Huntington. Figure 105 shows the smoothed differences between annual amounts of rainfall at Philadelphia and Boston from 1823 to 1927. The extreme swing is about twenty-four inches of rainfall (smoothed values) or nearly *two-thirds* of the annual rainfall at either of these places. The small inset curve at A shows the smoothed annual differences between Boston and Waltham near the great peak of 1868. Waltham is ten miles from Boston. The small scale shows a remarkable swing of about seven inches of rainfall in a distance of ten miles. The seasonal differences in rainfall between these two points are caused by differences between land and ocean temperatures (Chapter XI), hence we may deduce that the Boston-Philadelphia oscillations and trends in rainfall distribution are caused by changes in solar radiation and lagging ocean responses. The trends in Figures 73, 86, 95 and 98 also show the highly significant climatic variations going on at the present time.

In Figure 105 the positive values show more rainfall at Philadelphia and the negative values more at Boston. The great peaks

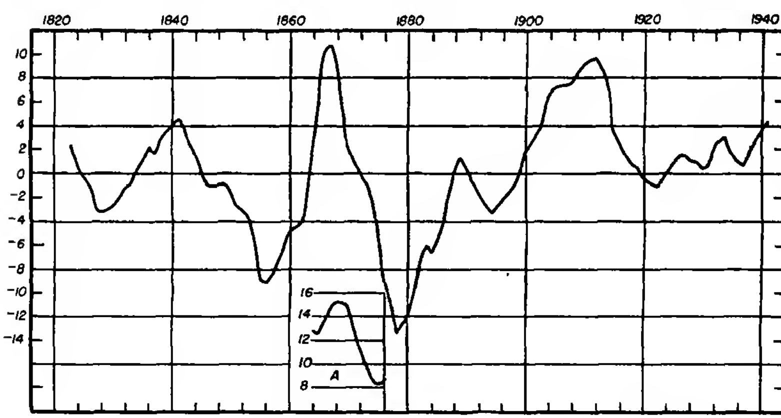


FIG. 105. Smoothed differences between annual amounts of rainfall at Philadelphia and Boston. Scales are in whole inches showing excess or deficiency at Philadelphia as compared with Boston. Inset scale shows excess of Boston over Waltham. Smoothed by formula given under Figure 71.

about 1841, 1866, 1889, and 1912 occurred near sunspot minima of 1843, 1867, 1889, and 1913. The intervening sunspot minima in 1856, 1878, 1901, and 1923 show generally an intermediate or extreme negative value. The trend therefore seems to be an accumulated effect of solar variations and heat-storage of the ocean, perhaps complicated by changes in vertical and horizontal movements of the waters. Whatever the cause, the possibilities in long-time trends are evident. The distribution shown by this curve may have left an indelible impression on the relative growth of suburban and agricultural areas surrounding these great cities, but this study is left to some investigator of the future.

The evidence seems to confirm the conclusion reached by Brooks that the mild climate of the ages was caused primarily by open oceans in the polar regions. The relatively high temperatures and deficiency of rainfall as compared with recent times seem to indicate a great reduction in the movement of cold air masses at the earth's surface from high to low latitudes, and this is difficult to explain if we assume that there were extensive land surfaces or frozen seas in the regions surrounding the poles. So far as North America is concerned, it is necessary to account for two phenomena: (1) If the Pacific Ocean in winter had been relatively much warmer in higher latitudes (compared to the continent) there certainly would have been cold air invasions, at least in early winter, into that part of the continent which is now the United States; and (2) Extensive land areas or frozen seas in higher latitudes would certainly have caused frequent invasions of cold air into middle latitudes of North America, at least in late winter and early spring. The absence of such invasions in the colder half of the year could have been due to open seas and absence of polar ice. This would be an adequate explanation of the uniform warmth and dryness of the climate during long periods of the past.

Applying this to the future, we can understand how one of these upward trends in temperature, combined with an exceptionally warm interval between sub-oscillations, might result in the disappearance of such large amounts of glaciers, polar ice, and snow that a marked change in climate would be started, with a further

progressive trend at a new level of continental warmth. Eastern Canada would become a year-round garden and there would be little summer rain in the United States except in the northeastern part. Greenland's ice would melt away under warm southwesterly winds; and the migration of millions of people to northern Canada, Alaska, and Greenland would proceed under conditions that would be difficult to imagine.

Finally, returning to the drought problem and to the conditions we have known in recent years, we may expect rainfall for the United States as a whole to continue to vary between limits of moderate deficiency and rather serious excess, with occasional droughts. These will probably be somewhat more severe than those in the immediate past if deforestation and cultivation continue to expand. But there is no good reason to think that occasional droughts will become a great deal worse than in recent climatic history so long as we have extensive frozen seas in the polar regions and snow-covered land in winter on the northern part of the continent. Nevertheless, our national rainfall in relation to crop production seems to be critically balanced at about twenty-nine inches. Serious consequences result from persistent national deficiencies of 10 per cent or more, and we have a problem that will require careful study and planning if we are to avoid disaster.

XX. CAUSES OF DROUGHT—A SUMMARY

In the introduction to this discussion of drought we considered two widely different points of view, classical and objective; and it seems clear from our analysis of national and regional data that drought cannot be explained satisfactorily as a chance combination of short spells of deficient rainfall. When we adopt the objective view and study the processes by which solar variations are translated into changes in the amount and distribution of rainfall, we see the oceans, and especially the Pacific Ocean, acting as the medium through which persistent controls of rainfall are maintained in the United States.

The dominant influence of the Pacific Ocean is quite apparent in the regularity of summer droughts on our west coast and in the permanency of certain arid regions in our Far West and Southwest. The influence of the Pacific is felt very strongly in the area between the Rocky Mountains and the Mississippi River, to a lesser degree as we proceed toward the east and northeast.

There are three major subdivisions of the country with regard to the control of rainfall variations. First is the region from the Rocky Mountains westward to the Pacific Coast. Over much of this area the rainfall in the growing season will usually be insufficient for crop farming, which must therefore depend on irrigation. The ranges, when not overstocked, are dependable for grazing. Fruit-drying is a great industry which shows the adjustment of agriculture to the regularity of the seasonal deficiency in rainfall. The lofty mountains, deep canyons, and giant trees give visible assurance of permanency. Even the droughts are dependable. Although the rainfall is more variable than elsewhere in the country, the amounts in summer, except at high elevations, are generally below the limit required for crop farming.

The second region extends from the Mississippi eastward to the Atlantic Ocean. Here rainfall is usually ample for agriculture. There are droughts, of course, but the driest years are characterized by rainfall that would be an abundance on the western

FIG. 106. At last, after centuries of despair in drought and famine, man has begun his first systematic, broad-scale scientific effort to wrest the secrets from the atmosphere. A radiosonde is sent aloft to signal back to earth the data on pressure, temperature, and moisture. (U.S. Weather Bureau photo)

ranges. In general, rainfall is less variable here than in the other two great subdivisions of the country. At first thought, it seems to be a paradox that the stability of the Pacific Ocean causes rainfall variations on the continent which are greatest near at hand and diminish with distance from the Pacific. But it is the resistance of the Pacific to continental temperature changes that causes the variations, and this resistance is felt less as we go farther away from the ocean.

The third region lies between the Mississippi and the Rocky Mountains. Here the rainfall is critical for agriculture, especially in the Great Plains. The influence of the Pacific Ocean is a vital factor. The rainfall of the region varies between extremes which are flood-producing at one time and dust-blowing at another. The north-south orientation of the mountain ranges permits the rainfall center to sweep back and forth over the entire region, bring-

ing rain to the north when the south is dry, and vice versa. We find strong evidence of the influence of solar variations in the seasonal and longer-time contrasts in rainfall distribution between the Gulf Coast and the interior and between the northern and southern parts of the region.

The rainfall picture for the country as a whole is understandable only from the objective point of view. The variations in rainfall which are associated with solar variations are of surprising magnitude. (Figs. 71, 73, 74, 86.) In this book, using the objective point of view, we have tried to put the drought puzzle together from the evidence at hand. A survey of the results shows that we need more concentrated study and collection of more data. The problem is so important in the national economy that considerable expenditure on studies of climatic change and drought occurrence would be justified, and the ultimate return would almost certainly greatly exceed the cost.

In the past there have been two distinct methods of dealing with rainfall. The first method uses daily reports of the amount of rain which falls at each of many points over the United States and adjacent territory. Reports from ships tell us whether or not it has rained at points on the ocean where the ships happen to be; but they do not report the amounts, for ships are not equipped with rain gages. The rainfall reports from the oceans and continent, together with air temperatures, barometer readings, winds, clouds and other elements, are entered on maps. The movements of rain areas are followed from day to day, and in some cases from hour to hour. These maps show rainfall in relation to storms and the movements of cold or warm air masses. By the second method, rainfall is tabulated by monthly and annual amounts, and the departures from the normal climate are noted. Nearly all of the discussions in this book have dealt with rainfall variations in neither of these classes. They are not shown on weather maps or in climatological tables.

We know, for example, that certain amounts of rain normally fall in Wisconsin and Louisiana. It is plotted on the daily weather maps and shown in the tables of rainfall for the two states. In some months and years these amounts are larger than in other

FIG. 107. The radiosonde ready to be released. The parachute floats back to earth from the high level where the balloon bursts, perhaps saving for another flight the little box which is a marvel of ingenuity, combining a small weather station and radio transmitter. Thanks to military developments during the war, this instrument is now a rawinsonde, that is, it now sends back wind direction and speed at successive heights in the atmosphere, in addition to pressure, temperature and humidity. (U.S. Weather Bureau photo)

months or years. While these records show that in general there may be more or less rain in Wisconsin or Louisiana, they are not charted or tabulated in a manner that shows clearly the sequences in the changes of distribution. The differences of rainfall between the two states are important (Fig. 86) because they are associated with drought. The distribution of rainfall is not a fixed element of climate, as one might conclude from maps of normal rainfall in the United States. It is a variable determined by the broad controls of sun, atmosphere, continents, and oceans.

There are two phases of the problem, the quantity and the distribution. They are not independent, but in certain respects quantity and distribution must be treated separately. The oceans are the important terrestrial factors, but in the absence of long, accurate, representative records of temperatures of the ocean surfaces, it is not possible to do more than show the nature of the problem and the line of attack. For example, nothing in this discussion has indicated what might be expected in the way of variations in rainfall in South Carolina. That would be a separate problem. We would have to study the South Carolina rainfall records in relation to the quantity and distribution of rainfall in the remainder of the country, with special attention to ocean-continent temperature contrasts, seasonal variations, oscillations and sub-oscillations, and the trend. This should lead to an understanding of how the "sun can pick out South Carolina" and cause a drought in that state while some adjoining areas might have normal rainfall.

If any one fact stands out in this study, it is that each local area will have to have its own drought problem solved separately from the others. This applies to larger areas when we consider the rainfall of the earth. The causes of rainfall are not the same in all parts of the earth, and therefore the causes of rain deficiency will not be the same. Near Tampa, Florida, for example, a large proportion of the rainfall is derived from local thundershowers. The occurrence of showers at Tampa is connected with relative temperatures of land and the nearby Gulf and Atlantic waters.

At St. Paul, Minnesota, however, most of the rainfall is cyclonic. St. Paul is in the meeting ground for warm moist air from the

south and cold air masses from Canada, and drought is traced to the absence of one or the other of these air masses. As a third example, the rainfall in many mountainous areas of the west is orographic; that is, the rainfall comes from prevailing winds against mountain slopes. The important factor in getting adequate rainfall is not the moisture content or the temperature of the air but the frequency with which the air is forced up the mountain slope so that condensation and precipitation take place.

In Europe, rainfall comes from the Atlantic Ocean in the normal flow of the prevailing westerlies. There is no north-south mountain range in western Europe as there is in North America. Therefore, the temperature of the Atlantic affects European rainfall directly; while in the United States east of the Rockies, moisture from the Atlantic and Gulf is controlled indirectly by the Pacific. The rainfall in Europe is probably dependent on relative Atlantic temperatures which determine the intensity and extent of the Atlantic high pressure area normally centered near the Azores (Fig. 59.) Like the Pacific high, the high near the Azores is variable in position and extent both from year to year and from season to season. The Mediterranean has summer droughts like those on our Pacific Coast. When the Atlantic high expands and shifts to the northward, much of Europe becomes dry.

In a study of great British droughts, Harding concluded that the controlling factors of the weather associated with drought in Great Britain are low barometer to the north of the British Isles and a relatively high barometer in the south of England; in other words, an extension of the high from the Azores toward and over England and the Channel. Most Italian droughts have been associated with the apparent joining of the Siberian and Atlantic high pressure areas across Europe. Richardson concluded that although the primary causes of drought were unknown, Australian droughts are connected with the temperature differences between the southern portion of Australia and the Great Southern Oceans along the 40th parallel of south latitude.

Even accurate records of temperatures from all parts of the oceans would not solve the problem. It is the *relative* temperature that matters. The Pacific Ocean is relatively cool in summer

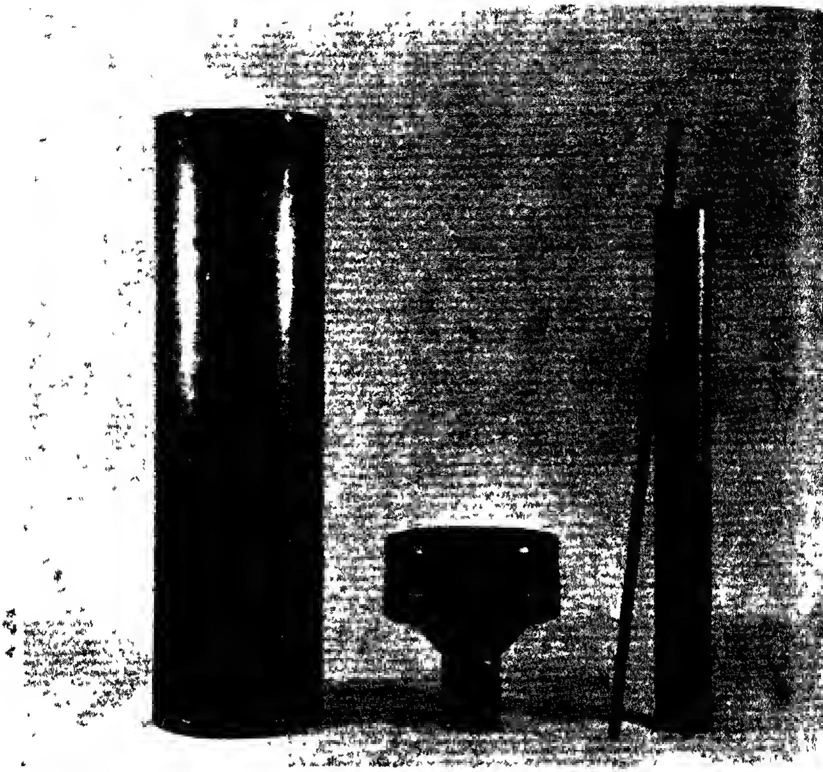


FIG. 108 A gage for measuring rain or snow The large container, when fitted with the cover in the middle, catches the rain. It is then poured into the small container at the right where it will be ten times as deep as in the large container, thus expanding the scale and making it easy to measure Snow is melted before it is measured. (U S Weather Bureau photo)

and relatively warm in winter, but its absolute temperature is actually slightly higher in summer. Hence, if we had all the ocean temperatures we need for our period of years from 1886 to 1944, we could trace in greater detail and with greater assurance the processes which lie between solar variation and drought, but we would have to depend to a large extent on the observed pressure, wind, temperature, and rainfall conditions over both the ocean and continent to determine whether or not the ocean temperatures actually were relatively cool or warm.

Even at the risk of too much repetition it seems important to

point out an apparent inconsistency in the discussions of droughts in the preceding chapters. The two ideas which appear to be contradictory are as follows: (1) That rising or high temperatures over the continent make the oceans relatively cool and cause a reduction in rainfall over the United States. This happens in the first half of the year when the sun is coming northward, and is accentuated during periods of increasing or maximum sunspots. (2) That relatively more rain falls in the United States in the first half of the year during periods of high solar activity (Fig. 71) and less when solar activity is low.

The first statement should be perfectly clear. One of the main points of this book is that a relatively cool ocean or a relatively warm continent causes less rain in the United States as a whole. It is true that more rain usually occurs in the first half of the year than in the second half when solar activity is high or increasing, but this does not necessarily mean that more than normal rain falls in the first half of the year, but rather that a larger portion of what may actually be a deficient annual rainfall occurs in the first half of the year. For example, in fifteen years with national rainfall below 95 per cent of normal, eight years had sunspot numbers averaging above 30; and in those eight years, the rainfall in the first half of the year was 93.8 per cent of normal and in the second half 88.2 per cent of normal. On the other hand, the remaining seven years, with sunspot numbers below 30, had 88.2 per cent of normal rainfall in the first half year and 92.8 per cent in the second half year. In the eight years with high solar activity a higher percentage of rainfall occurred in the first half of the year, and yet the rainfall in the first half was decidedly deficient. As another example, in seven years with very high sunspot numbers (80 or above), the rainfall in the United States in the first half year averaged 101.0 per cent and in the second half 90.8 per cent; and for the year as a whole they averaged only 95.9 per cent of normal.

Figures 74 and 86 show that in years with high solar activity a larger percentage of the rainfall goes farther into the interior. Wisconsin gets *relatively* more than Louisiana and Amarillo *relatively* more than Galveston. Figure 80 shows that April and May

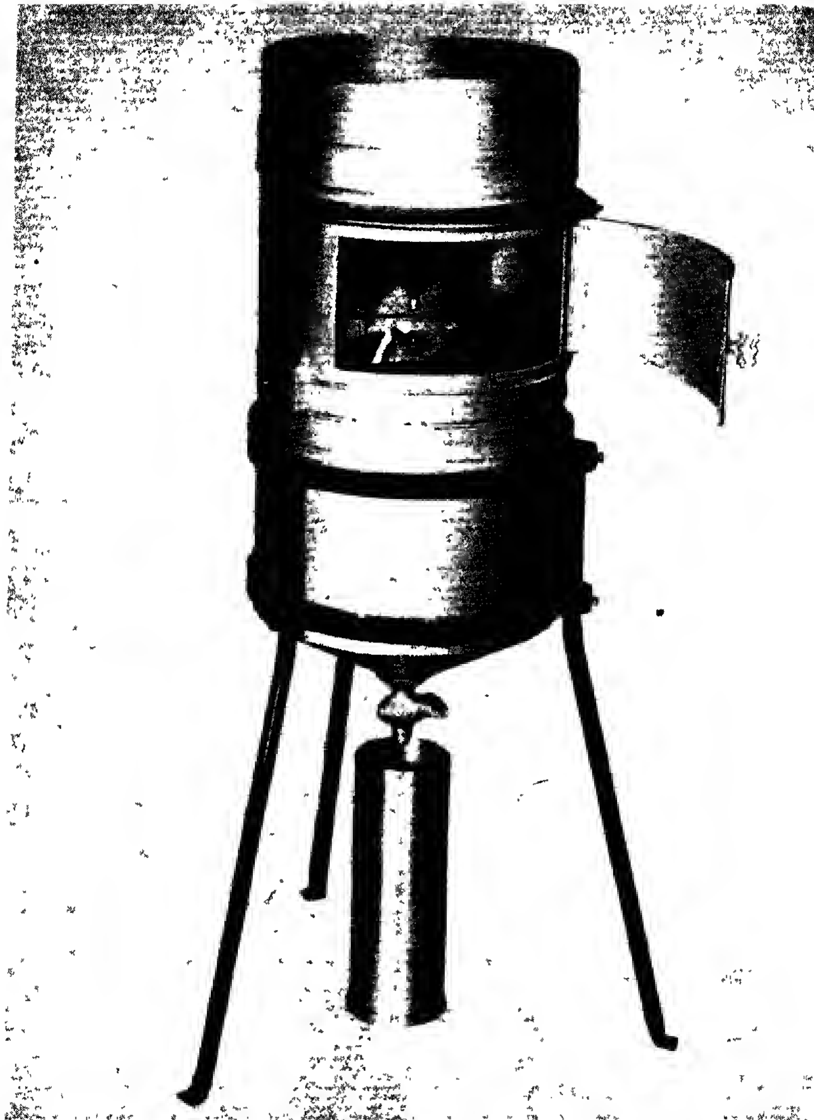


FIG 109 The automatic rain gage Rain caught in the top runs into the small tipping bucket inside One hundredth of an inch of rain is enough to tip the bucket, dump one side, and bring the empty side under the spout, and thus it tips back and forth and the record is electrically carried to a recording instrument in the weather office The rain water is drawn off at the bottom and measured in a container having one tenth the cross section of the large container. This measurement is used to check the automatic record. (U.S. Weather Bureau photo)

rainfall *increases* and September rainfall *decreases* with increasing solar activity. But the variation in yearly amounts is a composite of seasonal variations. When Amarillo gets relatively more than Galveston and Wisconsin relatively more than Louisiana, the total rainfall is likely to be deficient because Galveston normally has more rainfall than Amarillo, and Louisiana more than Wisconsin. The relative excess in the interior of the continent does not fully offset the deficiency in coastal states.

The drought problem is so complicated that it has been necessary to reduce it to simple terms of yearly rainfall on a national basis before discussing the basic controls. This does not lead to a simple solution of short-period regional or local drought problems, but it does provide a basis for their solution. The complexity and magnitude of the problem are shown clearly by the fact that the rainfall data for each month and year in the period from 1886 to 1944 for each of the states and sections into which the United States is divided would give us more than thirty thousand values to consider, and for local studies these tabulations would be too crude for our purposes. For example, the rainfall of Texas by itself shows seasonal and other cycles of large magnitude between the East Coast and the Panhandle (Fig. 74), and even over such short distances as fifty miles (Fig. 58).

The climate, as we know it, depends on the action of a very thin skin of atmosphere near ground level. The cold air which comes steadily, intermittently, or not at all, from Canada into the United States, is not deep; and usually the entire process does not represent a major portion of the atmosphere. But it is as important to us from an agricultural standpoint as though it involved the entire atmosphere. Oscillations and trends in temperature and rainfall are mainly the result of the actions of this thin skin of surface air. This does not mean that an extremely cold month in North Dakota, for example, requires a cooling of the entire atmosphere or even a large portion of the air in the Northern Hemisphere. In fact, the atmosphere as a whole, even over North America, may be warmer than usual. The cold weather in North Dakota may represent merely the southward movement of a thin surface layer of cold air from Canada.

The changes of climate shown in geologic records might even be explained by a persistent flow of a relatively thin skin of surface air from north to south (or its absence) without actually involving any fundamental change in the distribution of continents and oceans, in the constitution of the atmosphere, or even in solar radiation, except changes of the nature and magnitude that we observe today. For example, the change amounting to about 25° in mean monthly temperatures in winter (Fig. 98) is accomplished by nothing more dramatic than a seasonal change in the movement of a thin stream of cold air from Canada into the United States, yet this trend in December-February temperatures, if applied to the entire winter, would be almost of the same magnitude as the temperature changes in geologic times.

The presence (or absence) of cold surface air from Canada is important because of its close relation to the occurrence of drought in the United States. The great importance of the drought problem has been indicated in the discussion of economic effects, including the forced migration of large numbers of settlers from the plains region. In the United States the quantity of rainfall for the nation as a whole seems to be so critical for agriculture that a permanent reduction of only about 15 per cent from the 50-year average would require a major readjustment in our national economy, probably making it necessary for several millions of people to move to new homes in different areas. For example, there were seven years in our 59-year record when the national rainfall was at or below 90 per cent of the normal, and in these years the driest month averaged only 55 per cent of the normal for the country as a whole. Drought is far more severe in critical areas than the national deficiency of 10 per cent would indicate.

The processes by which solar variations are translated into rainfall variations may be summarized as follows: An increase in heat from the sun, either seasonally or in longer periods, tends to bring rain farther into the interior of the continent; a decrease causes more of the national rainfall to go to coastal areas. An increase or decrease in solar radiation, if sufficiently large, causes a considerable increase in the circulation of the atmosphere; this is greatest at the times when the sun's heat is normally increasing

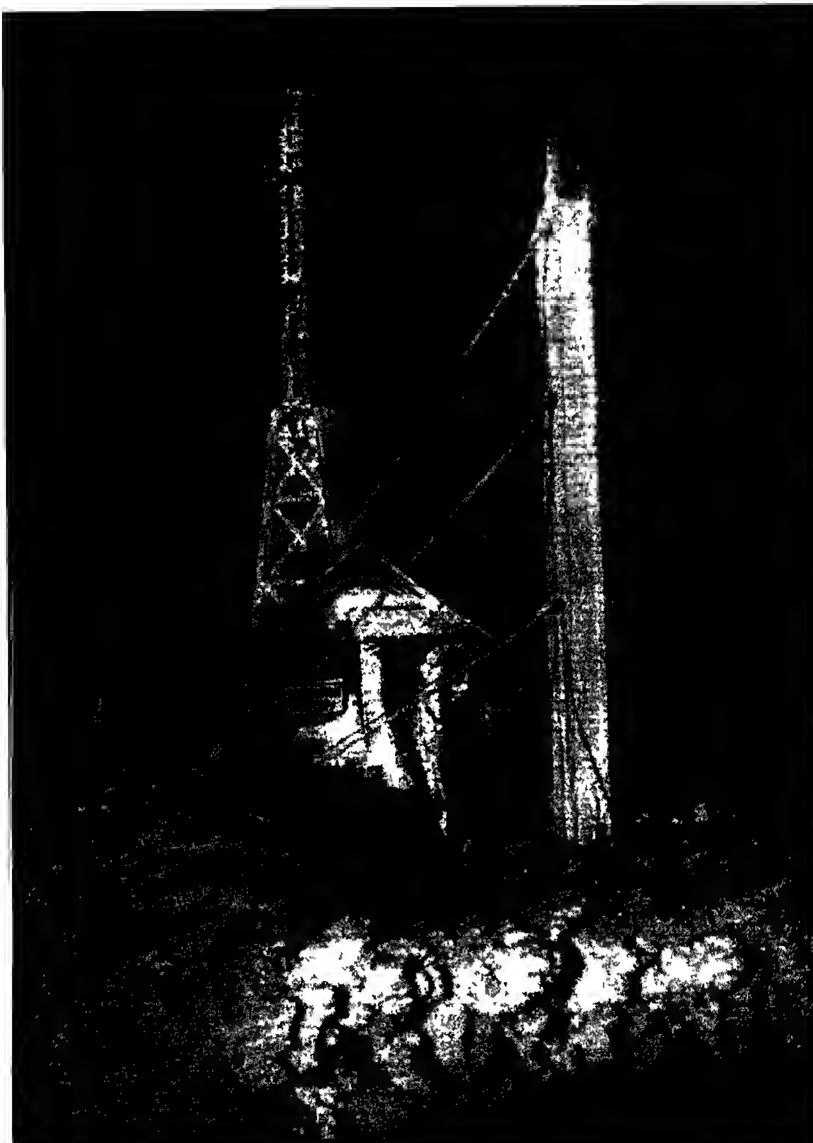


FIG. 110 In such places as this, weather observers go faithfully to their posts day after day and year after year to record the world's weather so that we may some day have a full understanding of drought and other weather phenomena. This is the weather observatory on top of Mt. Washington in New Hampshire, operated as a project of the United States Weather Bureau and Mount Washington Observatory Corporation. (U.S. Weather Bureau photo)

or decreasing. The increased circulation of the atmosphere in turn causes changes in the distribution of ocean temperatures. First, there is a cooling due to mixing of the waters; second, there is the effect of oceanic circulation. Therefore, when solar radiation increases or diminishes, the ocean temperatures lag behind and are relatively high or relatively low compared with continental temperatures. This causes changes in the amount and distribution of rainfall.

It is especially important that there is more than normal rainfall in the United States when pressure east of the Rocky Mountains is relatively high in the north and relatively low in the south. When this condition prevails, more Pacific air comes into the northern part of the continent than in the southern part. At the same time, the pressure on the Pacific Coast and presumably over the eastern North Pacific Ocean is relatively low. Conversely, when continental pressures are relatively low in the north and high in the south, and rainfall is deficient in the United States, Pacific pressure is high, especially in the north, presumably because less air comes from the Pacific into the northern part of the continent.

Because of the prevailing westerly circulation of the atmosphere in our latitude, the air must come over the mountains into the middle and eastern parts of North America; and if it does not go over in the north, it must accumulate and be forced over in the south. When this occurs, there are profound changes in the distribution of rainfall, and droughts are serious and widespread. The proportion of the westerly circulation which goes over in the south is clearly controlled by the seasonal changes in the relative position of the sun and also in a marked degree by the variations in solar radiation which are evidenced by the numbers of sunspots. Cyclonic storms move on tracks which are determined by the circulation of the atmosphere and the distribution of pressure. The storm tracks therefore change with the seasons and with the changes in solar radiation.

There are variations in solar radiation in addition to those indicated by the sunspot cycle. The accumulation of accurate measurements of solar variations undoubtedly will enable us to

treat rainfall in relation to these short variations and also in the longer periods which are associated with trends.

Rainfall in the United States is dependent on relatively low temperatures over the northern continent and relatively high temperatures over the northern Pacific. Ice and snow-covered land in the far north undoubtedly contribute in a large measure to the temperature differences in the thin skin of surface air masses. The cold air masses are needed to produce adequate rainfall. There is evidence that the droughty weather of the long warm periods of geological records was associated with open seas and with warmer conditions in the far north than exist at present. There is also evidence that cultivation of fields and other man-made changes in the land surface of the United States have contributed to relatively higher average continental temperatures in spring and summer, and that this in turn is probably responsible for a small but significant part of the downward trend in rainfall. There have been, and probably will continue to be, temporary reversals of this trend, owing chiefly to the long-term changes in solar radiation and in the temperature of the eastern North Pacific Ocean.

In the past our failures to treat the drought problem successfully in the United States have been owing to two factors: (1) we did not realize that the great air stream which crosses the United States from west to east, and which is forced to hurdle our western mountains, is the basic control of our rainfall; and (2) neither the daily weather maps, which are absolutely essential in forecasting day-to-day weather, nor the methods of presenting our climatological data, which are essential for other purposes, are satisfactory for a treatment of droughts and other phenomena which represent temporary changes in climate. The future must bring us two necessary aids: (1) more accurate and longer-continued measurements of solar radiation, including the ability to predict these variations with at least a fair degree of accuracy; and (2) a different technique of studying and predicting weather phenomena, such as droughts, which are intimately dependent on basic controls of sun, atmosphere, continents, and oceans.

Weather forecasters use the term "synoptic" in connection with

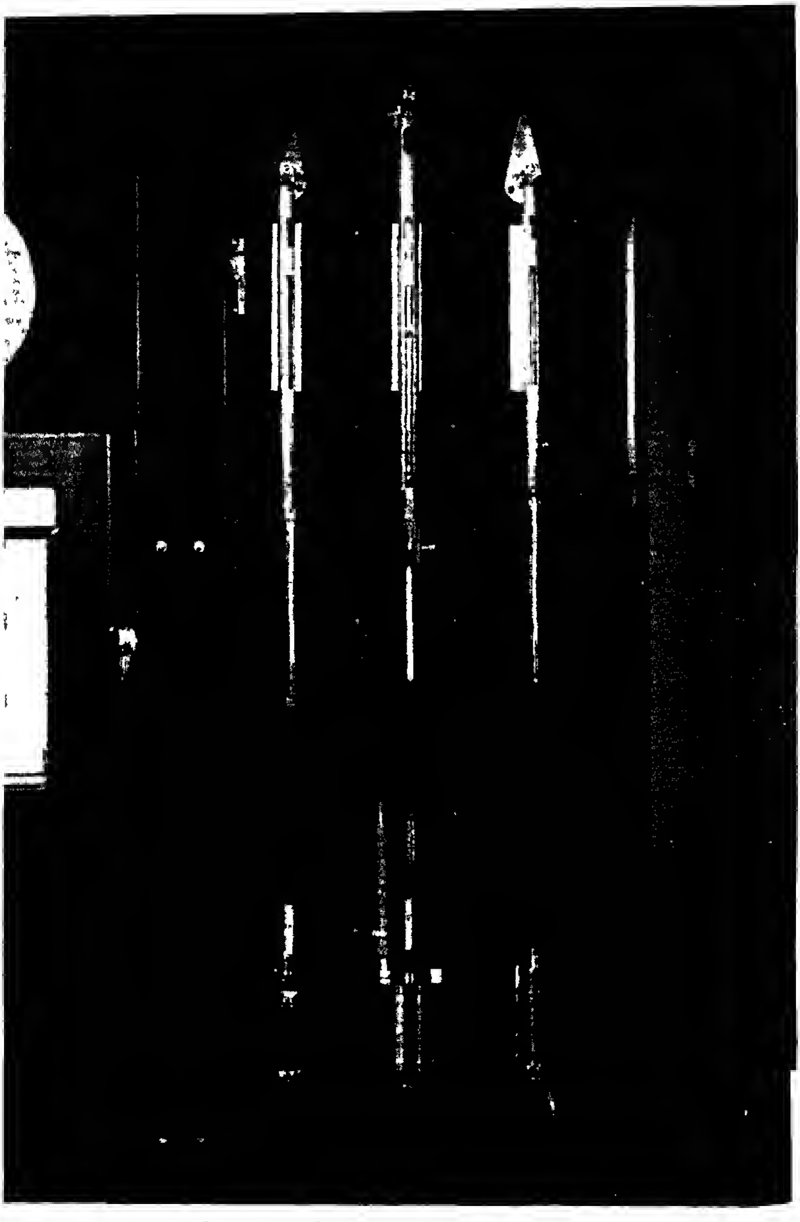


FIG. 111. These are barometers of the mercurial type which have been used for many years to give measurements of atmosphere pressure accurate to approximately one thousandth of an inch of a column of mercury. (U.S. Weather Bureau photo)

weather observations and maps. "Synoptic" meteorology usually covers a large area but only considers short sequences of conditions. Meteorologists should accept the idea that climate is changeable like the weather and is under control of the same basic forces. The technique necessary to deal with such phenomena is "synoptic climatology," as illustrated by the treatment of the drought problem in this book.

It is not the intention of this book to propose that droughts be predicted by means of sunspots, or Pacific temperatures, or any other single factor. Sunspots have been used to show the solar influence because sunspots are the only dependable indication of solar variations we have for any considerable period of time in the past. If solar variations in the sunspot cycle have an effect on the distribution of rainfall, so will other solar variations of shorter and longer periods.

Drought is one extreme of the hydrologic cycle. At the other extreme we have excessive rainfall and floods. The rainfall variations discussed here apply to both drought and flood, but there is a difference. When the northern branch of the Pacific airflow across the Rockies is very strongly predominant, there is deficient rainfall in parts of the United States because the prevailing winds blow across the continent to the ocean, and little moist air comes in. When the southern branch predominates, the rainfall is deficient again. It is only in the intermediate stage, when there is a moderate amount of cold air from Canada and when plenty of moist air from the Gulf and Atlantic is also present, that we have conditions most favorable for excessive rain along the border between the two air masses. The treatment of floods involves a problem slightly different from the drought problem.

When variations of temperature and other conditions of the atmosphere are correlated with sunspot numbers in a long sequence of years, there appears an occasional reversal which is known as a "change of phase." Years near times of maximum sunspots may be generally colder than years near sunspot minima. Two or more solar cycles may occur between changes of phase. A change of phase marks the end of a trend. When solar radiation is progressively increasing through several solar cycles,

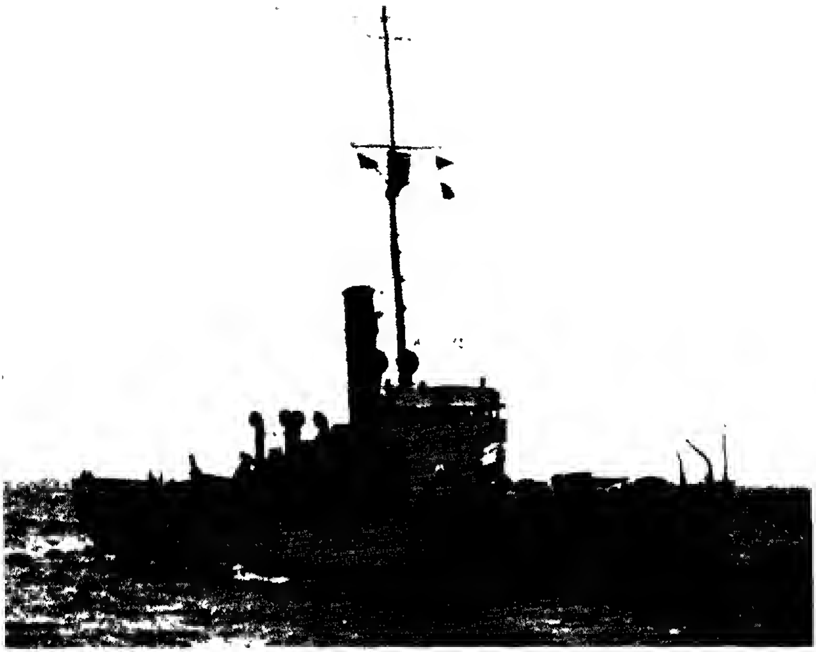


FIG. 112. A "weather ship" (U.S. Coast Guard Cutter with U.S. Weather Bureau Observers) stationed at a fixed point in the Atlantic to take and transmit complete weather observations, including frequent upper air soundings. Accurate observations from the oceans are essential for an understanding of drought and similar phenomena. (U.S. Weather Bureau photo)

the temperature depression of the warm sub-oscillation predominates; when solar radiation is progressively diminishing, the temperature depression of the cold sub-oscillation predominates. This causes the principal temperature depression of the solar cycle to shift from sunspot maxima to minima, and vice versa. Temperatures at Bismarck, North Dakota, for example, show a change of phase in the late eighteen-eighties, and another seems to be in progress at the present time.

World temperatures, which have been rising generally in the present century, seem to have started downward again, beginning a new trend. The change of phase of the late eighteen-eighties and the beginnings of the new one about 1940 are in evidence in Figure 97. It may be several years before this new trend is defi-

nitely established. Changes in amount and distribution of rainfall are closely associated with these long-term temperature trends.

Observers of world temperature are suspicious that this new trend means that we will have colder years and presumably somewhat more rainfall. After the sunspot maximum in the late nineteen-forties, when another cold sub-oscillation begins, the evidence may be more conclusive. At the present time, in consideration of our relatively short series of accurate weather records, this is a matter for speculation.

In conclusion, the writer regrets that it is necessary to say that the problem of drought is not completely solved. A great deal of work remains to be done. The changes of the future may bring new phases of the problem which will have to be studied.

The pattern of world rainfall is vital to human civilization. Time has scrawled a bold but cryptic message, alternately dry and moist, on the rocks, on the fossils of flora and fauna of the ages, and finally on the gravestones of civilizations. The scrawl continues, and at last our thermometers, rain gages, barometers, rawinsondes, and other instruments are beginning to decipher the story. (Figs. 106-112.) The record shows unmistakable evidence of the interactions of atmosphere, oceans, and continents, under the basic control of the sun.

In the future, farmers will not have to gaze despairingly into a clear sky, wondering if a few clear days will continue into a disastrous drought. Even if we are never able to control the climate, much will be gained by knowing what to expect. Droughts are not mere chance occurrences; they are part of a physical process which can be measured and studied and predicted with increasing precision as our observations of the sun and the upper air and the oceans continue to accumulate.

APPENDIX A

TABLE I

Average Precipitation and Temperature in the United States

Table I gives averages of monthly and annual precipitation, by states or sections, for the 55 years, 1886-1940. All values are for individual states, except the New England section and the states of Maryland and Delaware, which are each given a section. These data are from the Climate and Crop Weather Division of the Weather Bureau as compiled by J. B. Kincer. The table is followed by a group of small charts (Figs. 113 to 118) showing normal temperature and precipitation by states for each month of the year.

STATE OR SECTION	JAN.	FEB	MAR	APR.	MAY	JUNE	JULY	AUG	SEPT	OCT	NOV	DEC	YEAR
Alabama	4 96	5 36	5 84	4 45	3 91	4 31	5 53	4 70	3 26	2 72	3 20	4 89	53 13
Arizona	1 25	1 34	1 03	57	32	33	2 09	2 28	1 28	82	94	1 28	13 53
Arkansas	4 42	3 49	4 68	4 82	4 84	4 06	3 75	3 56	3 36	3 01	3 93	4 11	48 03
California	4 84	4 33	3 66	1 70	1 00	31	07	09	46	1 22	2 31	4 05	24 04
Colorado	79	97	1 29	1 78	1 84	1 39	2 19	1 95	1 37	1 13	78	89	16 37
Florida	2 77	3 12	3 15	2 85	4 00	6 73	7 37	6 99	6 68	4 15	2 20	2 76	52 77
Georgia	4 30	4 90	4 91	3 65	3 49	4 48	5 86	5 29	3 70	2 71	2 64	4 13	50 06
Idaho	2 22	1 74	1 80	1 44	1 60	1 34	64	60	1 02	1 45	1 95	2 11	17 91
Illinois	2 38	1 97	3 16	3 44	4 03	3 91	3 22	3 35	3 62	2 52	2 66	2 14	36 40
Indiana	3 19	2 43	3 70	3 57	3 99	3 87	3 32	3 39	3 32	2 72	3 05	2 79	39 34
Iowa	1 08	1 07	1 72	2 76	4 02	4 32	3 52	3 58	3 75	2 18	1 64	1 12	30 76
Kansas	69	1 00	1 44	2 53	3 81	3 92	3 14	3 12	2 76	1 88	1 29	84	26 42
Kentucky	4 48	3 53	4 69	4 02	3 94	4 13	4 10	3 75	2 91	2 59	3 45	3 77	45 36
Louisiana	4 87	4 50	4 64	4 67	4 46	4 89	6 07	5 17	3 82	3 23	3 86	5 22	55 40
Maryland (& Delaware)	3 37	3 17	3 71	3 56	3 74	3 87	4 44	4 40	3 44	3 01	2 65	3 10	42 46
Michigan	2 03	1 76	2 06	2 38	3 19	3 09	2 70	2 78	3 15	2 67	2 51	2 07	30 38
Minnesota	80	76	1 16	2 14	3 15	3 98	3 27	3 18	2 76	1 82	1 14	80	24 96
Mississippi	5 16	4 92	5 66	4 92	4 28	4 33	5 07	4 18	3 05	2 57	3 61	5 29	53 04
Missouri	2 46	2 09	3 19	3 90	4 70	4 64	3 55	3 81	3 99	2 80	2 69	2 15	39 97
Montana	87	71	94	1 14	2 07	2 56	1 42	1 06	1 31	1 02	91	86	14 87
Nebraska	52	71	1 10	2 38	3 30	3 52	2 95	2 77	2 03	1 38	76	65	22 07
Nevada	1 21	1 05	97	77	84	49	38	47	43	60	64	99	8 84
New England	3 55	3 21	3 66	3 38	3 33	3 44	3 75	3 83	3 79	3 48	3 48	3 37	42 27
New Jersey	3 65	3 54	3 82	3 67	3 70	3 86	4 71	4 72	3 84	3 60	3 18	3 56	45 85
New Mexico	59	73	75	86	1 15	1 25	2 46	2 39	1 73	1 11	66	70	14 38
New York	3 01	2 75	3 06	3 02	3 42	3 67	3 90	3 76	3 49	3 27	3 09	2 93	39 37
No Carolina	3 80	3 99	4 19	3 62	4 08	4 72	5 93	5 64	3 90	3 27	2 67	3 79	49 60
No Dakota	49	49	75	1 42	2 21	3 45	2 49	1 96	1 46	1 03	58	50	16 83
Ohio	3 09	2 53	3 49	3 23	3 63	3 87	3 80	3 41	2 95	2 49	2 72	2 71	37 92
Oklahoma	1 44	1 37	2 11	3 32	4 54	3 72	2 81	3 00	3 07	2 86	2 02	1 61	31 87
Oregon	4 07	3 16	2 86	2 03	1 72	1 28	43	40	1 20	1 99	3 61	4 04	26 79
Pennsylvania	3 24	2 94	3 50	3 45	3 84	4 14	4 29	4 17	3 45	3 17	2 89	3 08	42 16
So Carolina	3 59	4 23	3 83	3 23	3 58	4 79	5 80	5 76	4 01	2 91	2 33	3 51	47 57
So Dakota	55	57	1 09	2 07	2 80	3 31	2 48	2 20	1 49	1 12	62	56	18 86
Tennessee	4 82	4 37	5 41	4 42	4 17	4 19	4 46	4 07	3 01	2 77	3 56	4 52	49 77
Texas	1 89	1 82	2 03	2 94	3 65	3 11	2 61	2 41	2 97	2 54	2 27	2 27	30 51
Utah	1 21	1 27	1 39	1 16	1 14	57	87	98	1 00	1 07	90	1 12	12 68
Virginia	3 29	3 15	3 70	3 38	3 90	4 20	4 65	4 51	3 23	3 06	2 52	3 03	42 62
Washington	4 94	3 68	3 39	2 40	1 97	1 74	75	79	1 79	2 98	5 01	5 66	35 10
W Virginia	3 68	3 24	3 85	3 53	4 09	4 41	4 58	4 10	3 01	2 84	2 77	3 20	43 30
Wisconsin	1 42	1 30	1 81	2 51	3 54	3 96	3 43	3 30	3 62	2 44	1 83	1 37	30 53
Wyoming	81	78	1 13	1 55	2 02	1 57	1 35	1 09	1 10	1 08	68	73	13 89
United States	2 27	2 12	2 43	2 47	2 81	2 88	2 76	2 61	2 39	2 06	2 02	2 28	29.10

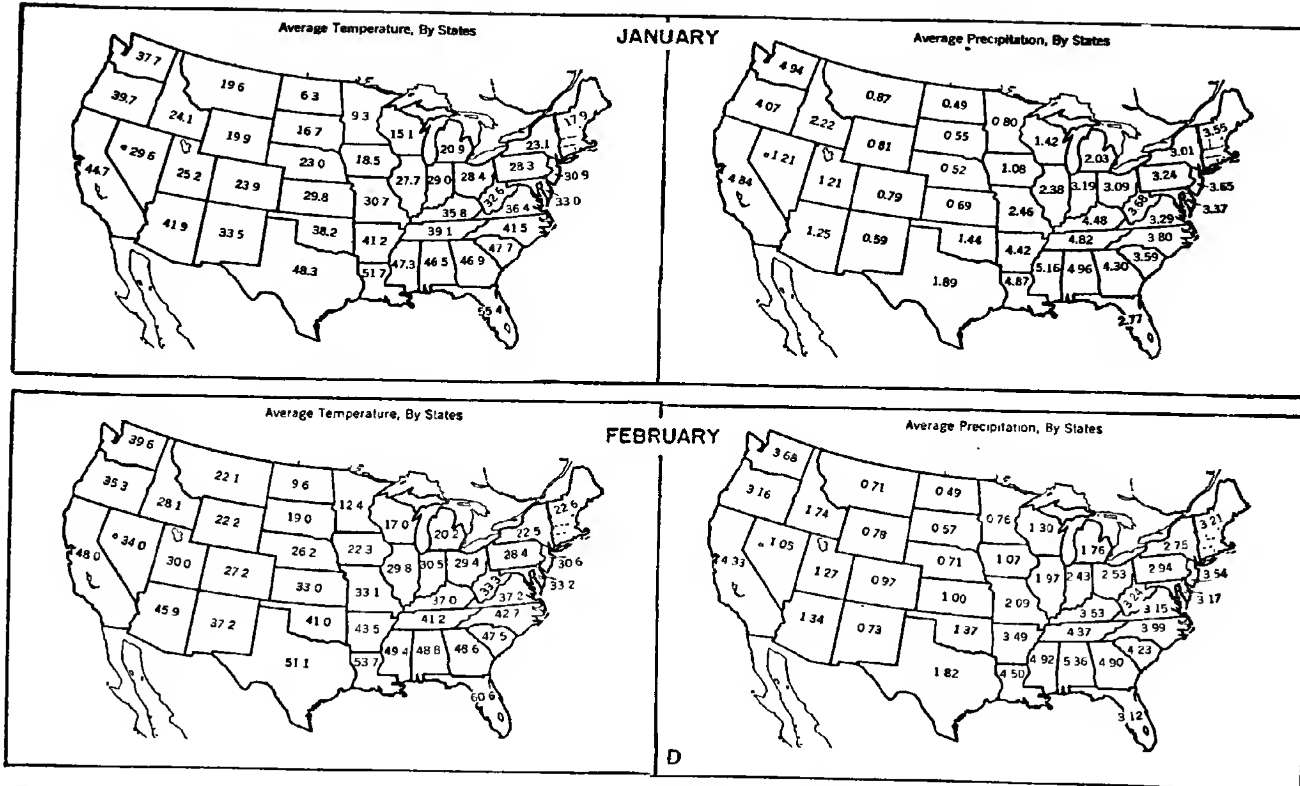


FIG. 113. Normal temperature and precipitation in the United States. Above, January; below February. (U.S. Weather Bureau)

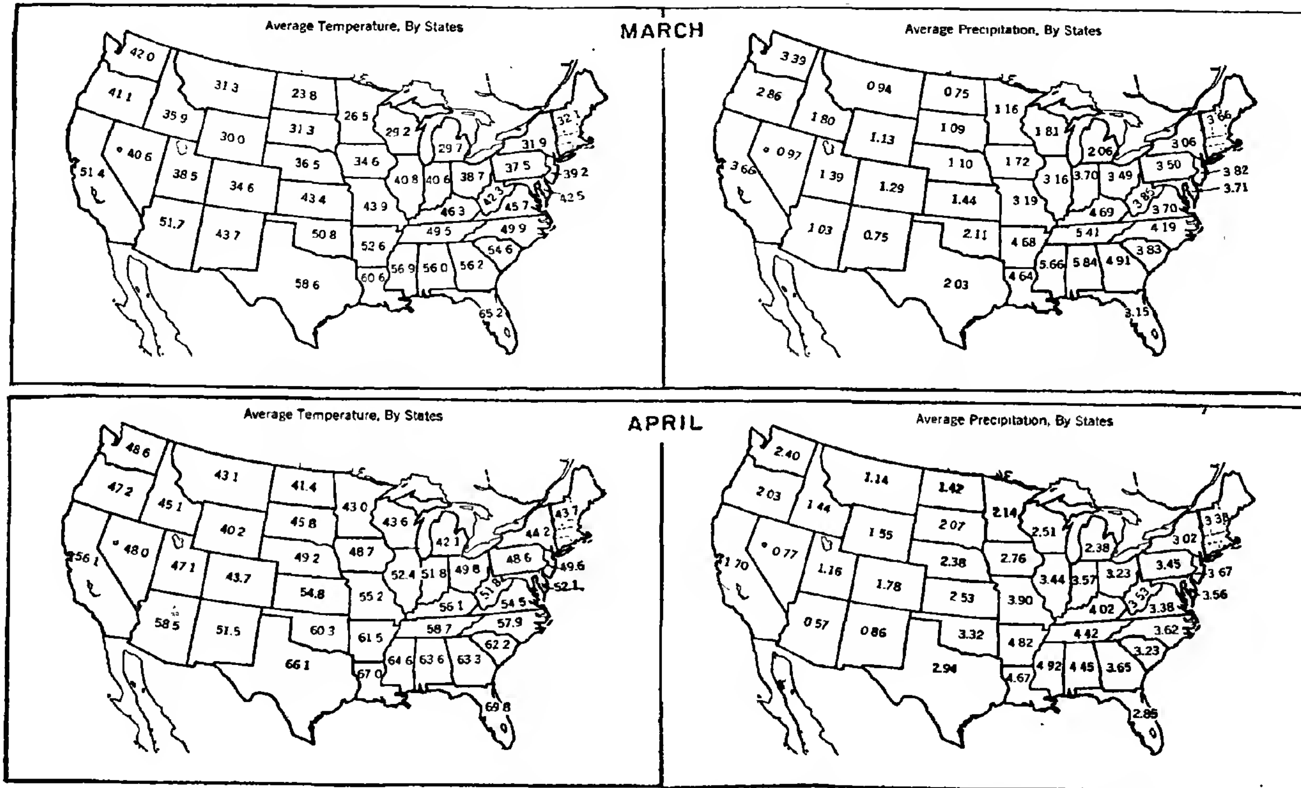


FIG. 114. Normal temperature and precipitation. Above, March; below, April. (U.S. Weather Bureau)

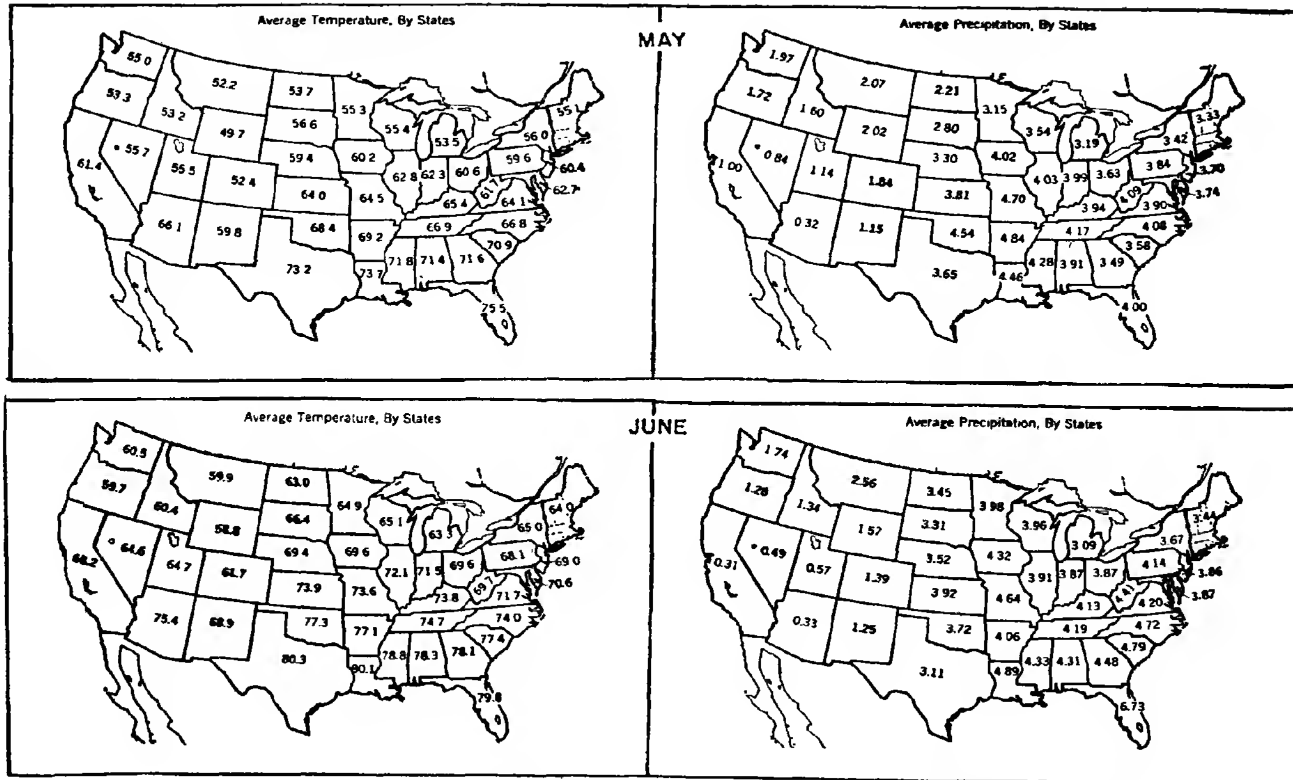


Fig. 115. Normal temperature and precipitation. Above, May; below, June. (U.S. Weather Bureau)

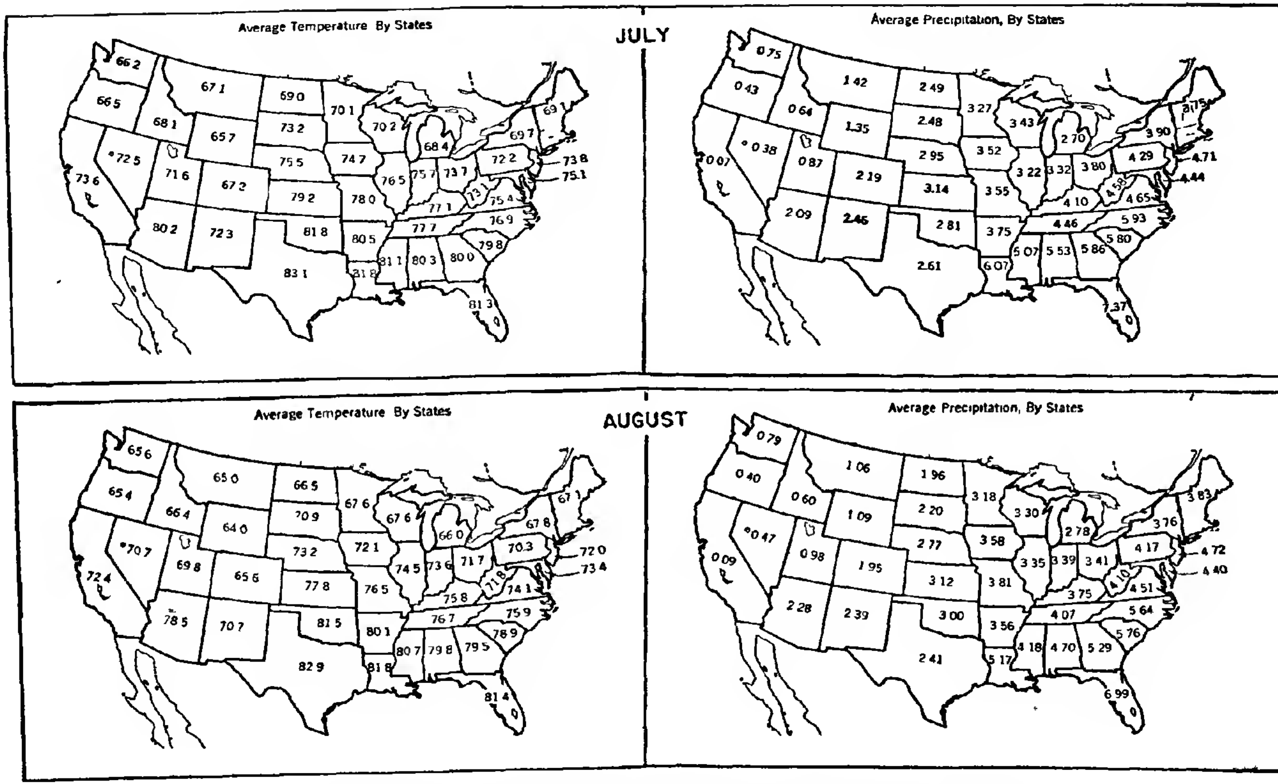


FIG. 116. Normal temperature and precipitation. Above, July; below, August.

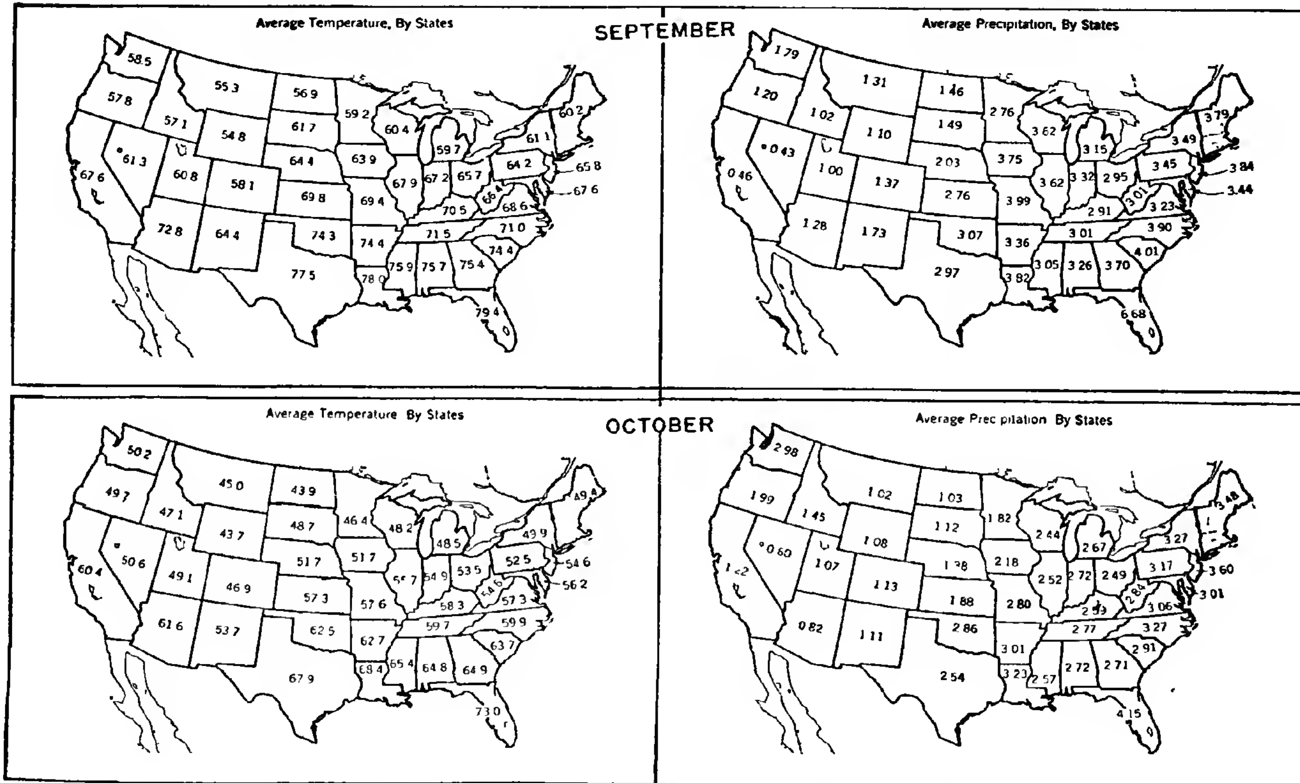


FIG 117 Normal temperature and precipitation Above, September, below, October

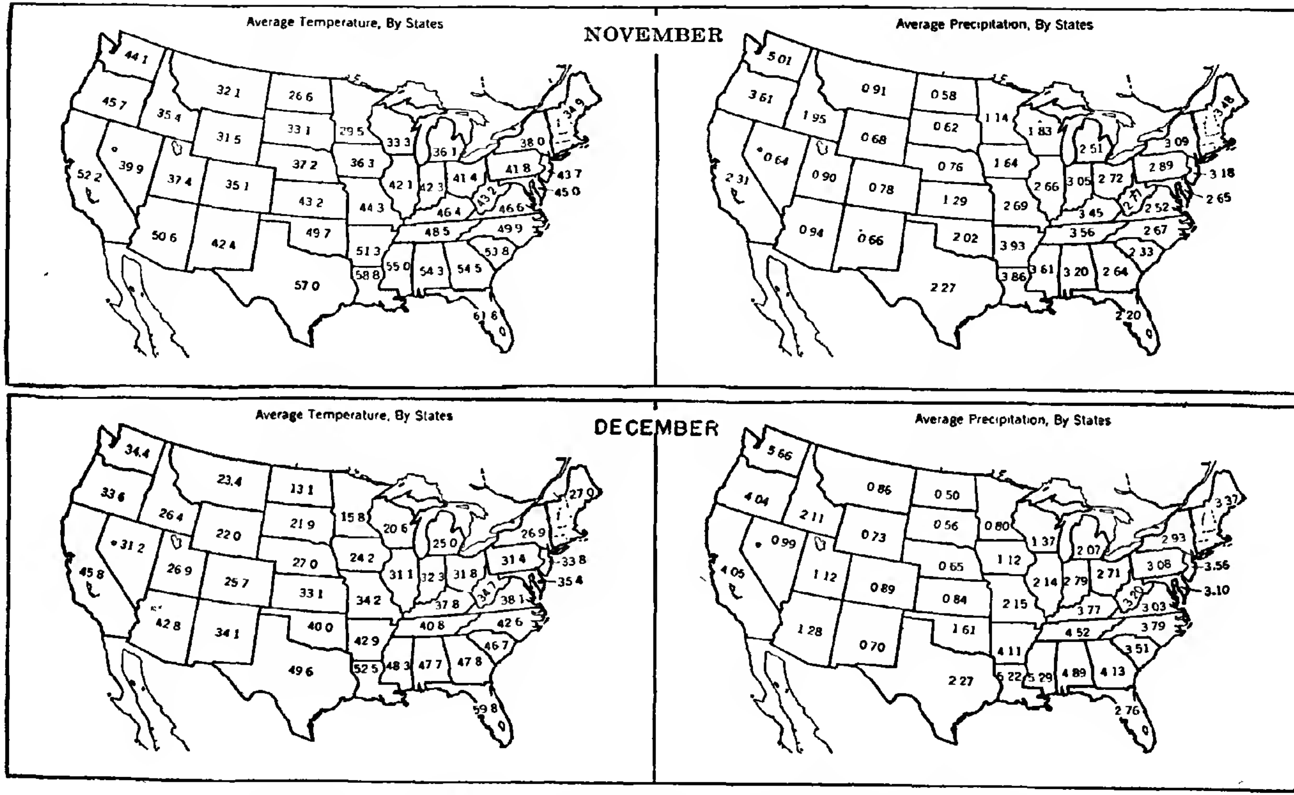


Fig. 118. Normal temperature and precipitation. Above, November; below, December.

APPENDIX B

TABLE II

Precipitation by Months for the United States as a Whole, 1886-1945

Averages for each month for each state or section are weighted according to state or section area. The sums of the averages for all states determined in this manner are expressed as percentages of the normal national rainfall. For example, the number 137 for January 1886 indicates that the sums of the weighted averages of all states was 137 per cent of the national normal for January.

YEAR	JAN.	FEB.	MAR	APRIL	MAY	JUNE	JULY	AUG	SEPT.	OCT.	NOV.	DEC.	ANNUAL
1886	137	77	107	110	69	106	84	98	108	70	95	85	96
1887	88	128	64	85	82	93	102	109	100	91	70	129	95
1888	108	92	121	77	116	109	85	130	88	103	129	101	105
1889	121	75	86	80	98	109	118	78	108	90	135	95	99
1890	125	130	109	109	105	96	81	110	118	124	65	77	104
1891	111	145	124	90	82	115	115	93	70	60	104	126	103
1892	97	85	99	111	137	113	103	99	69	76	116	108	102
1893	64	115	95	115	115	85	79	95	96	81	105	82	94
1894	100	115	99	97	91	81	75	89	110	95	52	103	92
1895	137	62	82	85	102	106	109	94	66	57	114	105	94
1896	100	96	95	102	103	92	121	75	115	105	139	65	100
1897	101	121	147	96	76	98	103	85	67	90	104	107	99
1898	102	77	97	82	114	103	106	118	97	123	107	74	100
1899	108	99	112	73	94	106	107	85	63	118	96	90	96
1900	75	114	93	139	88	104	114	92	121	129	113	70	104
1901	80	94	92	102	97	90	85	114	109	74	69	107	93
1902	59	112	114	73	106	99	114	81	120	95	148	123	103
1903	93	148	124	79	103	101	111	115	90	87	79	61	100
1904	77	104	122	86	93	107	107	103	100	81	49	91	95
1905	93	108	118	117	134	115	127	101	108	110	110	103	113
1906	111	79	132	82	111	106	121	128	119	101	114	125	111
1907	117	83	101	93	125	106	108	98	105	100	115	116	106
1908	79	130	89	109	148	106	107	110	78	99	81	75	102
1909	119	136	91	95	109	112	107	91	94	77	140	117	107
1910	95	97	42	83	95	86	92	86	89	99	79	74	85
1911	109	98	73	118	70	75	105	119	111	124	102	130	102
1912	83	88	138	134	104	97	108	114	105	104	72	92	104
1913	123	89	123	82	88	92	95	72	135	125	114	110	103
1914	108	99	77	109	90	97	89	122	89	120	77	115	99
1915	125	131	61	92	137	109	128	136	113	90	100	117	112
1916	170	80	81	83	103	112	119	97	82	100	72	96	100
1917	92	83	100	108	93	83	91	92	91	67	45	66	85
1918	100	79	76	117	91	77	83	94	104	141	114	115	98
1919	83	123	109	97	116	105	114	96	98	173	137	78	110
1920	96	74	114	131	99	102	97	129	103	106	111	118	107
1921	89	80	103	113	89	103	104	98	109	70	113	97	98
1922	88	115	144	123	112	93	104	85	66	83	100	114	102
1923	103	89	98	114	111	113	99	111	118	121	93	123	108
1924	87	84	91	92	88	97	85	84	120	70	65	113	90
1925	98	80	62	82	68	101	97	77	117	146	106	70	91
1926	104	94	96	92	78	86	104	122	134	120	137	115	106
1927	74	125	105	126	104	110	104	106	104	115	126	118	109
1928	53	87	95	117	82	145	109	120	90	107	102	75	100
1929	101	96	114	119	128	91	95	69	116	125	100	92	104

YEAR	JAN.	FEB.	MAR.	APRIL	MAY	JUNE	JULY	AUG.	SEPT.	OCT.	NOV.	DEC.	ANNUAL
1930	111	81	79	72	113	80	66	75	98	113	113	58	88
1931	70	86	94	83	82	74	98	103	85	91	120	148	94
1932	143	103	92	84	84	106	93	109	89	121	103	129	104
1933	98	89	104	103	120	50	105	110	103	80	49	113	94
1934	80	77	96	72	64	89	75	87	123	80	147	82	88
1935	103	78	112	109	134	111	95	96	104	78	103	78	101
1936	123	122	86	81	81	65	85	85	126	100	58	123	94
1937	161	102	87	107	81	108	94	100	83	128	101	105	104
1938	92	111	130	109	116	109	122	79	104	60	98	74	101
1939	108	136	84	87	78	115	86	103	68	76	51	77	90
1940	85	138	92	121	79	103	91	116	82	84	140	127	104
1941	90	84	85	117	94	133	114	103	130	183	87	120	111
1942	68	93	101	116	112	122	92	116	116	103	111	126	107
1943	93	57	117	79	123	111	92	80	79	90	70	76	90
1944	83	124	125	129	106	101	84	113	100	66	132	91	104
1945	77	128	129	123	101	121	112	101	142	93	108	118	113

TABLE III

Precipitation—Eastern Division

Precipitation amounts for states east of the Mississippi River for each year, 1886-1945, are expressed as percentages of normal. For example, the number 104 for Alabama in 1886 means that the precipitation in Alabama in that year was 104 per cent of the normal.

YEAR	ALABAMA	FLORIDA	GEORGIA	ILLINOIS	INDIANA	KENTUCKY	MARYLAND AND DELAWARE	MICHIGAN	MISSISSIPPI	NEW ENGLAND	NEW JERSEY	NEW YORK	NORTH CAROLINA	OHIO	PENNSYLVANIA	SOUTH CAROLINA	TENNESSEE	VIRGINIA	WEST VIRGINIA	WISCONSIN	REGION
1886	104	103	105	94	101	98	113	104	106	107	101	95	105	100	102	92	104	113	92	102	102.0
1887	90	98	100	92	92	87	88	101	83	112	105	101	105	92	97	91	90	102	84	105	96.8
1888	101	104	117	107	101	98	102	94	96	132	118	109	111	102	109	114	97	112	111	102	107.4
1889	92	96	97	98	92	79	137	88	72	117	137	122	102	88	125	98	91	143	99	87	100.3
1890	94	102	95	103	126	129	109	113	106	119	108	126	93	133	121	89	115	102	137	115	111.0
1891	100	90	100	91	102	109	121	101	106	106	105	97	109	102	108	103	106	112	106	85	101.4
1892	107	92	102	113	106	97	98	111	109	92	92	103	95	98	98	100	109	93	88	114	102.0
1893	95	103	93	94	105	98	91	114	97	95	105	107	108	104	105	110	91	108	92	97	100.6
1894	89	101	99	80	81	77	89	92	90	85	102	98	94	78	103	105	85	84	80	91	90.2
1895	94	91	103	86	79	85	80	89	90	97	81	86	101	75	79	103	86	90	76	73	88.4
1896	85	97	89	102	103	98	85	105	82	97	92	99	96	104	99	95	94	100	100	105	96.7
1897	89	106	98	100	103	103	106	103	90	110	112	102	93	102	101	99	102	92	96	91	99.4
1898	93	94	109	129	116	115	99	106	103	120	114	111	101	115	108	105	101	105	110	92	107.3
1899	90	100	89	91	89	102	96	93	85	95	100	87	105	90	97	99	96	99	98	100	94.5
1900	125	115	115	97	95	98	86	106	123	108	93	96	97	87	88	107	103	93	90	115	104.0
1901	105	112	115	72	78	78	106	92	94	113	113	110	126	83	108	119	94	117	106	86	101.0
1902	93	97	100	115	102	98	116	107	91	111	123	109	89	98	112	98	89	95	99	107	102.2
1903	94	105	107	95	93	91	111	108	88	99	123	110	101	96	110	107	95	103	94	117	101.6
1904	74	91	73	103	97	77	86	98	78	95	95	98	87	94	96	85	82	85	77	103	89.3
1905	104	115	101	101	109	105	103	110	120	87	91	99	104	107	103	94	102	102	102	115	104.4
1906	106	102	109	103	100	107	113	103	103	96	102	95	119	98	101	115	108	117	102	112	105.3
1907	104	93	97	112	114	105	115	101	102	102	113	97	97	115	108	100	98	104	120	99	102.9
1908	91	90	100	98	87	92	94	98	104	84	93	85	117	91	94	111	91	108	95	96	96.0
1909	110	92	97	119	120	113	87	107	110	96	90	91	95	113	89	95	101	89	97	103	101.5
1910	85	98	87	88	95	111	88	84	89	84	86	94	96	95	92	96	90	97	91	70	90.5

1911	99	91	95	107	102	103	102	110	113	92	110	93	85	113	108	84	106	96	108	121	101.3
1912	125	124	126	97	103	105	104	103	123	99	100	97	96	100	104	114	109	96	100	106	107.2
1913	98	91	93	96	112	104	91	95	108	96	101	101	104	119	102	99	95	99	111	107	100.7
1914	85	93	91	78	80	92	85	99	88	82	86	92	94	93	91	91	88	86	92	106	90.1
1915	101	106	99	115	105	114	103	101	102	96	103	104	101	108	105	102	109	94	102	107	103.9
1916	100	90	87	101	102	100	95	112	97	96	83	96	97	98	97	93	102	91	105	110	98.1
1917	101	78	95	88	93	101	96	90	85	94	89	98	101	96	99	91	103	94	102	89	93.6
1918	106	95	98	103	103	89	89	97	94	92	81	97	99	96	97	97	95	102	104	97	97.3
1919	123	109	110	102	99	115	112	99	131	102	114	101	96	107	111	97	115	98	110	109	107.6
1920	121	109	120	89	94	103	106	96	119	115	112	103	112	99	96	109	113	108	97	98	106.1
1921	86	85	82	111	116	109	89	105	91	88	84	90	86	113	99	90	100	82	105	101	95.5
1922	111	108	110	93	98	98	94	106	112	100	90	100	113	98	83	122	109	106	95	103	103.3
1923	115	95	105	103	109	119	95	95	134	95	88	90	91	103	93	97	115	96	104	86	101.5
1924	89	117	108	98	96	94	109	98	76	84	97	94	111	99	102	120	93	111	109	108	99.9
1925	85	98	82	89	88	90	82	84	93	97	91	105	75	90	90	76	81	76	94	90	85.1
1926	115	114	101	118	111	110	103	109	106	93	97	102	87	116	102	89	110	97	114	115	106.0
1927	86	77	81	135	125	118	95	104	105	108	108	115	90	114	112	89	111	98	113	101	103.6
1928	105	114	119	102	93	100	106	110	97	96	101	99	113	93	100	130	106	101	100	108	104.9
1929	144	112	140	115	119	107	100	103	114	93	94	109	125	122	105	135	120	109	108	92	114.1
1930	87	113	91	76	75	61	56	74	90	81	77	82	76	70	68	85	80	59	59	82	79.4
1931	81	82	75	103	97	92	91	98	99	97	81	97	88	101	88	74	87	89	98	97	91.2
1932	120	100	116	99	109	108	111	109	128	103	100	107	105	98	92	113	119	105	101	83	106.3
1933	91	105	83	96	103	111	116	100	95	106	108	95	79	102	108	75	102	93	112	89	97.1
1934	104	100	96	90	75	82	103	84	101	102	99	89	108	70	93	93	95	107	87	100	97.1
1935	93	99	89	114	100	126	112	94	97	91	92	96	97	107	96	89	100	110	118	99	99.9
1936	114	109	117	83	86	83	105	89	84	119	103	102	121	88	101	120	94	106	97	83	100.3
1937	110	111	105	101	117	110	122	103	104	112	104	111	106	118	110	108	112	125	115	90	108.8
1938	91	82	84	111	104	101	98	104	92	120	115	105	97	104	95	85	100	99	98	136	101.3
1939	112	103	99	96	99	104	106	99	102	92	95	88	99	100	87	97	100	99	101	87	97.9
1940	103	99	95	77	83	85	105	107	114	103	107	102	92	101	103	90	86	107	104	108	98.2
1941	87	111	86	106	83	73	79	105	87	78	82	82	78	83	81	93	74	74	84	112	88.4
1942	100	101	106	113	105	110	111	115	91	106	110	111	104	101	113	99	101	115	112	116	106.7
1943	98	91	94	104	95	83	81	105	78	96	85	100	87	94	90	92	84	84	93	97	92.2
1944	106	101	108	93	86	89	100	95	114	95	102	95	107	88	95	102	109	106	103	95	99.2
1945	106	105	108	127	126	113	121	116	111	116	114	125	110	118	117	116	115	111	116	115	114.7

TABLE IV

Precipitation—Middle Division

The percentages given here are similar to those in Table III except that Table IV refers to states between the Mississippi River and the Rocky Mountains.

YEAR	ARKANSAS	IOWA	KANSAS	LOUISIANA	MINNESOTA	MISSOURI	MONTANA	NEBRASKA	NORTH DAKOTA	OKLAHOMA	SOUTH DAKOTA	TEXAS	REGION
1886	89	80	97	101	109	91	84	104	101	52	97	74	87.1
1887	78	85	88	89	99	87	107	98	107	76	122	91	94.8
1888	95	102	88	98	100	101	91	100	94	87	90	139	105.3
1889	95	81	111	75	75	95	60	100	68	97	97	125	97.0
1890	128	95	80	101	95	98	68	77	103	124	81	113	96.3
1891	92	107	117	95	98	93	115	137	117	93	98	100	105 6
1892	120	118	109	112	110	111	104	109	109	124	126	96	108.6
1893	100	89	76	89	98	98	105	71	94	80	89	67	84.9
1894	102	71	78	92	88	80	102	62	92	80	82	91	86.8
1895	93	87	106	99	88	100	79	85	103	110	86	108	95 9
1896	78	121	108	85	125	101	109	116	134	74	111	90	105.2
1897	96	87	92	95	109	101	106	105	95	96	99	89	96 8
1898	118	101	120	115	96	135	110	92	96	124	77	93	103 6
1899	86	93	99	77	116	94	100	88	104	113	99	94	97.2
1900	102	113	105	121	114	97	93	107	113	102	105	138	113.1
1901	73	79	80	90	97	64	102	103	115	71	112	73	87.1
1902	108	142	130	85	112	112	103	132	115	127	103	111	116.1
1903	93	115	118	89	128	101	105	120	114	92	111	108	108.7
1904	90	92	117	79	101	105	75	106	106	93	88	98	95.6
1905	129	118	116	137	131	117	92	141	112	124	130	137	123 8
1906	116	102	108	88	121	98	125	117	119	115	130	103	112.1
1907	103	102	100	106	92	102	119	90	85	106	99	111	103 8
1908	102	114	122	106	117	109	129	119	110	149	119	108	116 7
1909	92	130	117	97	114	113	134	110	107	85	120	77	104.7
1910	94	64	74	90	59	94	108	75	74	59	79	70	78 3
1911	103	102	92	112	116	93	125	95	109	91	96	95	102 4
1912	95	93	100	119	90	97	117	96	120	89	95	86	98 0
1913	112	97	87	119	102	95	104	98	87	103	92	118	103 7
1914	89	103	89	97	114	86	102	93	112	81	113	124	105.0
1915	110	128	153	96	114	124	127	160	114	142	151	105	124.8
1916	88	94	90	92	113	101	125	84	118	91	109	81	98 1
1917	85	90	74	73	86	80	97	92	64	70	88	53	74.6
1918	93	106	104	99	98	94	93	100	95	105	113	95	98.5
1919	113	119	97	126	110	100	73	112	92	108	104	149	112 8
1920	113	103	100	114	103	94	98	110	91	114	123	112	106.3
1921	99	104	91	86	91	111	98	92	115	94	99	94	97.0
1922	97	97	109	119	90	99	102	90	118	106	113	108	104.2
1923	125	96	120	131	80	105	122	126	105	141	116	132	113 4
1924	77	102	91	70	100	100	92	94	101	87	94	77	88 8
1925	88	91	94	95	94	97	110	93	99	89	83	84	92 5
1926	102	107	93	120	99	107	93	93	91	122	92	119	104.5
1927	137	95	122	108	99	138	139	106	127	124	122	91	113.8
1928	105	116	126	102	102	114	88	102	106	114	92	95	102.1
1929	96	98	105	115	85	116	88	102	85	111	109	102	99.9
1930	97	84	101	96	91	78	83	116	88	96	94	97	93 4
1931	98	115	97	96	89	100	68	86	89	99	75	96	90 6
1932	106	104	89	114	86	95	109	92	102	106	101	112	103 1
1933	102	81	83	100	82	94	105	91	80	96	79	85	89 4
1934	88	87	75	107	81	87	75	64	56	86	66	88	80.0
1935	119	107	107	103	103	120	73	102	107	115	89	123	106 0
1936	71	84	69	83	73	73	76	65	52	71	58	101	77.6
1937	115	89	79	107	103	93	87	79	101	88	91	88	91.2
1938	102	117	103	91	114	102	112	95	91	104	92	89	99.6
1939	104	80	75	92	87	95	84	69	82	81	79	80	82.8
1940	93	97	96	134	101	81	100	74	101	103	79	114	100 0
1941	95	116	138	108	116	105	116	104	135	143	108	141	123.2
1942	103	106	125	103	116	115	114	114	111	125	126	109	113.6
1943	73	101	93	93	109	97	102	78	109	90	94	84	92.9
1944	114	121	142	112	120	97	104	124	128	113	129	118	115.4
1945	140	112	114	111	110	133	100	103	88	131	95	110	110.2

TABLE V

Precipitation—Western Division

The percentages given here are similar to those in Tables III and IV except that Table V refers to states from the Rocky Mountains westward to the Pacific Coast.

YEAR	ARIZONA	CALIFORNIA	COLORADO	IDAHO	NEVADA	NEW MEXICO	OREGON	UTAH	WASHINGTON	WYOMING	REGION
1886	74	81	107	93	85	111	125	77	117	70	89.6
1887	85	77	86	90	59	106	157	50	125	58	81.4
1888	91	89	73	92	87	102	121	70	118	93	91.0
1889	99	139	83	82	141	76	111	100	90	93	111.5
1890	115	105	73	106	151	89	83	67	96	106	107.7
1891	62	93	121	89	160	102	108	107	123	115	113.5
1892	73	108	94	112	120	66	85	77	94	86	98.1
1893	77	97	78	112	106	86	110	92	117	77	96.2
1894	82	108	87	112	129	73	121	90	124	85	106.7
1895	98	93	111	78	84	108	93	84	101	121	94.5
1896	96	119	91	117	113	92	123	80	131	108	109.9
1897	93	79	118	113	113	115	106	115	123	92	104.2
1898	91	43	95	83	79	97	78	84	94	90	79.1
1899	64	94	89	106	98	76	115	94	128	100	96.8
1900	58	83	88	92	86	94	91	66	104	79	82.5
1901	79	92	86	84	129	101	92	80	98	87	96.7
1902	76	101	84	95	83	69	111	73	114	70	88.7
1903	66	86	84	98	77	78	93	81	90	92	83.5
1904	70	127	99	99	128	100	121	90	92	103	107.9
1905	207	90	110	87	90	145	78	108	82	117	107.1
1906	123	161	120	117	148	110	110	145	101	128	133.3
1907	115	135	99	115	134	112	118	127	91	105	119.4
1908	120	78	104	95	75	88	78	117	92	124	94.4
1909	108	176	127	127	114	89	122	153	102	117	128.6
1910	75	70	87	98	66	66	100	88	95	87	81.0
1911	121	123	117	101	97	124	85	103	76	100	104.2
1912	97	93	114	124	89	97	121	112	99	132	105.3
1913	93	105	108	114	125	107	102	103	90	121	109.4
1914	127	130	117	96	107	135	98	108	94	88	109.5
1915	122	141	118	108	90	122	97	106	98	138	112.4
1916	128	145	113	117	111	111	106	126	96	97	117.3
1917	97	69	89	110	76	66	90	94	96	99	87.5
1918	113	102	114	97	105	105	77	112	86	116	103.5
1919	154	89	104	89	80	145	97	94	88	79	95.6
1920	101	111	108	107	101	103	98	131	97	102	105.7
1921	113	108	117	106	94	114	101	123	105	90	104.9
1922	98	121	95	89	109	75	89	117	70	102	102.4
1923	132	59	129	108	99	135	87	108	84	139	102.8
1924	68	71	83	75	62	74	81	84	79	91	74.6
1925	99	88	103	109	115	96	88	115	80	112	102.4
1926	123	113	103	102	73	121	95	98	91	105	98.1
1927	124	115	123	134	89	97	116	131	119	130	115.5
1928	74	78	103	78	55	105	83	85	91	102	79.0
1929	84	63	110	78	66	114	74	108	67	108	81.2
1930	116	77	105	95	111	102	71	120	78	106	99.0
1931	146	102	85	84	91	127	91	80	120	83	97.8
1932	101	65	86	110	94	112	99	106	126	96	94.5
1933	88	84	92	104	76	89	105	84	135	87	90.6
1934	78	75	66	90	81	70	96	75	109	78	81.5
1935	115	92	96	69	98	103	76	86	83	88	91.6
1936	107	109	97	92	116	94	86	134	93	94	105.4
1937	97	121	88	112	101	104	129	117	123	111	109.4
1938	96	125	117	109	134	101	98	120	83	110	114.6
1939	93	67	65	79	97	91	79	90	91	73	82.4
1940	124	156	102	127	124	104	124	124	104	102	121.3
1941	151	154	136	124	158	196	114	163	98	128	145.8
1942	70	100	114	112	85	109	113	99	95	111	99.1
1943	92	101	87	92	109	80	90	111	78	89	91.8
1944	102	100	101	89	97	101	74	119	73	112	97.8
1945	84	114	103	123	128	69	119	144	111	125	111.0

BIBLIOGRAPHY

Note. Books, atlases, charts, published papers and other sources of information on precipitation and its variations, including descriptions of individual droughts which were published currently in the past, are so numerous that it is impracticable to give references to all of them in this list. The following include those from which information was drawn in the preparation of this book, and also a number of recent books on meteorology and climatology. Those preceded by an asterisk contain a number of additional references to the literature.

Abbot, C. G. *Smithsonian Miscellaneous Collections*, Vol. 94, No. 12, 1935; Vol. 95, No. 12, 1936.

——— "Weather Predetermined by Solar Variation," *Smithsonian Miscellaneous Collections*. Vol. 104, No. 5, 1944.

——— and Fowle, F. E. "Volcanoes and Climate," *Smithsonian Miscellaneous Collections*, Washington, 1913.

——— "The Sun Makes the Weather," *The Scientific Monthly*, March and April 1946.

Alexander, W. H. "The Distribution of Thunderstorms in the United States," *Monthly Weather Review*, 1924, also 1935.

Antevs, Ernst. *The Last Glaciation*, New York, 1928.

Archibald, E. D. "Barometric Pressure and Sunspots," *Nature*, 1879.

——— "Droughts, Famines, and Forecasts in India," *Monthly Weather Review*, 1900.

Aughey, Samuel. *Sketches of the Physical Geography and Geology of Nebraska*, Omaha, 1880.

*Baker, O. E. *Atlas of American Agriculture*. Kincer, J. B. Part II, Section A, Precipitation and Humidity. U.S. Department of Agriculture, Washington, 1922.

Baur, F. "Zur Frage der Realität der Schwankungen du Solar Konstante," *Meteorologische Zeitschrift*, 1932.

Bennett, H. H. *Soil Conservation*, New York, 1939.

Berry, F. A., Bollay, E., and Beers, N. R. *Handbook of Meteorology*, New York, 1945.

Bigelow, F. H. "The Relations Between the Meteorological Elements of the United States and the Solar Radiation," *American Journal of Science*, 1908.

Blair, T. A. *Climatology, General and Regional*, New York, 1942.

——— *Weather Elements: A Text in Elementary Meteorology*, New York, 1942.

Blanford, H. F. *The Climates and Weather of India*, London, 1889.

——— "The Paradox in the Sunspot Cycle in Meteorology," *Nature*, 1880.

Block, L. H. "The Record-Breaking Drought, Heat and Dust Storms of 1934," *Bulletin of American Meteorological Society*, 1934.

Bollinger, C. J. "The 22-Year Solar Pattern of Rainfall in Oklahoma and Kansas," *Bulletin of the American Meteorological Society*, November 1945.

Bowie, E. H. "The Long Dry Season of 1929 in the Far West," *Monthly Weather Review*, 1929.

BIBLIOGRAPHY

Bowie, E. H. and Weightman, R. H. "Types of Storms of the United States and their Average Movements," *Monthly Weather Review*, Sup. No. 1, 1914.

——— "Types of Anticyclones of the United States and their Average Movements," *Monthly Weather Review*, Sup. No. 4, 1917.

Bowman, Isaiah. "Our Expanding and Contracting Desert," *Geographical Review*, New York, 1935.

Brands, G. J. *Meteorology: A Practical Course in Weather*, New York, 1944.

Briggs, L. J. and Belz, J. O. "Dry Farming in Relation to Rainfall and Evaporation," *Bull. U.S. Bureau of Plant Industry*, 1910.

Brisbin, J. S. *The Beef Bonanza*, Philadelphia, 1881.

Broggi, J. A. "La Desglaciación Actual de los Andes del Perú," *Bol. Soc. Geol. Perú*, Lima, 1943.

Brooks, C. F. "Ocean Temperatures in Long-Range Forecasting," *Monthly Weather Review*, 1918.

*Brooks, C. E. P. *Climate Through the Ages*, London, 1926.

——— "Arctic Ice and British Weather," *Monthly Weather Review*, 1928.

——— "The Role of the Oceans in the Weather of Western Europe," *Quarterly Journal of the Royal Meteorological Society*, 1930.

——— and Glasspoole, J. "The Drought of 1921," *Quarterly Journal of the Royal Meteorological Society*, 1922.

Bruckner, E. *Klimaschwankungen Seit 1700*, Vienna, 1890.

Buchan, A. "The Rainfall in Scotland in Relation to Sunspots," *Journal of the Scottish Meteorological Society*, 1903.

Byers, H. R. *General Meteorology*, New York, 1945.

Cameron, D. C. "Great Dust Storm in Washington and Oregon," April 21-24, 1931, *Monthly Weather Review*, 1931.

Caudle, F. L. *Workbook in Elementary Meteorology*, New York, 1944.

Chambers, M. J. "The Drought of 1933-34 in New Mexico," *Monthly Weather Review*, 1935.

*Chapline, W. R. and Cooperrider, C. K. "Climate and Grazing," *Climate and Man*, Washington, 1941.

Choun, H. F. "Duststorms in the Southwestern Plains," *Monthly Weather Review*, June 1936.

Chronological List of Famines for All India, Madras Administration Report, 1885.

Chu, Co-Ching. "Climatic Pulsations During Historic Time in China," *Geographical Review*, New York, 1926.

Clayton, H. H. "The Influence of Rainfall on Commerce and Politics," *Popular Science Monthly*, December 1901.

——— "World Weather Records," *Smithsonian Miscellaneous Collections*, Vol. 79, 1927. Vol. 90, 1934.

——— "Solar Activity and Long-Period Weather Changes," *Smithsonian Miscellaneous Collections*, Vol. 78, No. 4, 1926.

——— "The Sunspot Period," *Smithsonian Miscellaneous Collections*, Vol. 98, No. 2, 1939.

——— "The Atmosphere and the Sun," *Smithsonian Miscellaneous Collections*, Vol. 82, No. 7, 1930.

——— *World Weather*, New York, 1923.

——— "Sunspot Changes and Weather Changes," *Smithsonian Misc. Coll.* Vol. 104, No. 19, March 1946.

Cline, I. M. "Summer Hot Winds on the Great Plains," *American Meteorological Journal*, 1894-1895, *Bulletin Philosophical Society*, 1894.

——— "Hot Winds in Texas, May 29 and 30, 1892," *American Meteorological Journal*, 1892-1893.

Clough, H. W. "The Long-Period Variations in the Length of the 11-Year Solar Period, and Concurrent Variations in Terrestrial Phenomena," *Bulletin of the American Meteorological Society*, April 1943.

——— "The Weather of the Present Century—Past and Prospective," *Bulletin of the American Meteorological Society*, 1934.

Cole, H. S. "Droughts in Arkansas," *Monthly Weather Review*, 1933.

Conrad, V. *Fundamentals of Physical Climatology*, Milton, Mass., 1942.

Croy, Homer. "The Rainmakers," *Harper's Magazine*, September 1946.

Dallas, W. L. "The Prediction of Droughts in India," *Report of the International Meteorological Congress Held in Chicago*, 1893.

Day, P. C. "Relative Humidities and Vapor Pressures over the United States, Including a Discussion of Data from Recording Hair Hygrometers," *Monthly Weather Review*, Sup. 6, 1917.

Dick, Everett. *The Sod-House Frontier*, New York, 1937.

Disterdick, F. L., "Severe Sandstorm in Eastern Wyoming, January 18, 1933," *Monthly Weather Review*, 1933.

Donn, W. L. *Meteorology, with Marine Applications*, New York, 1946.

*Douglass, A. E. *A Method of Estimating Rainfall by the Growth of Trees*. Carnegie Institute of Washington, Pub. 192, 1914.

Dutt, Romesh. *Famines in India*, London, 1900.

Eliot, John. *Droughts and Famines in India*, Bulletin 11, U.S. Weather Bureau, 1895.

Fletcher, R. D. "The General Circulation of the Tropical and Equatorial Atmosphere," *Journal of Meteorology*, September 1945.

Freeman, O. W. "Evidence of Prolonged Droughts on the Columbia Plateau Prior to White Settlement," *Monthly Weather Review*, 1929.

Fremont, J. C. *Report of the Exploring Expedition to the Rocky Mountains in the Year 1842, and to Oregon and North California in the Years 1843-'44*. Washington, 1845.

Golder, F. A. *On the Trail of the Russian Famine*, 1927.

Grant, H. D. *Clouds and Weather*, New York, 1944.

Hand, I. F. "The Character and Magnitude of the Dense Dust Cloud Which Passed Over Washington, D.C., May 11, 1934," *Monthly Weather Review*, 1934.

Harding, Charles. "Great British Droughts" (abstract), *Monthly Weather Review*, 1923.

Harrison, L. P. *Meteorology*, New York, 1942.

Harrison, M. C. "An Unusual Texas Duststorm, March 24-25, 1933," *Monthly Weather Review*, 1933.

Haurwitz, B. "Atmospheric Ozone As a Constituent of the Atmosphere," *Bulletin of the American Meteorological Society*, 1938.

——— and Austin, J. M. *Climatology*, New York, 1944.

Haynes, B. C. *Meteorology for Pilots*, Washington, 1943.
*Helland-Hansen, Bjorn, and Nansen, Fridtjof. "Temperature Variations in the North Atlantic Ocean and in the Atmosphere," *Smithsonian Miscellaneous Collections*, Vol. 70, No. 4, Washington, 1920.
Hellman, G. "Untersuchungen Uber die Schwankungen der Niederschlage," *Veroffentlichungen des Konigl. Preuss. Meteoro. Instituts*, 1909.
Henry, Alfred J. "Secular Variations of Precipitation in the United States," *Bulletin of American Geographical Society*, New York, 1914.
———— "Seasonal Forecasting of Precipitation—Pacific Coast," *Monthly Weather Review*, 1921.
———— "The Great Drought of 1930 in the United States," *Monthly Weather Review*, 1930.
———— "The Calendar Year as a Time Unit in Drought Statistics," *Monthly Weather Review*, 1931.
Hewson, E. W. and Longley, R. W. *Meteorology, Theoretical and Applied*, New York, 1944.
Hill, S. A. "Variations in Rainfall in Northern India," *Indian Meteorological Memoirs*, I, No. VII.
Holden, W. C. "West Texas Droughts," *Southwestern Historical Quarterly*, 1928.
Holzman, Benjamin. "The Hydrologic Cycle," *Climate and Man*, 1941.
Hovde, M. R. "The Great Duststorm of November 12, 1933," *Monthly Weather Review*, 1934.
Hovgaard, W. "The Norsemen in Greenland. Recent Discoveries at Herjolfones," *Geographical Review*, New York, 1925.
Hoyt, J. C. "Drought of 1930," *Journal New England Water Works Association*, 1931.
Humphreys, W. J. "Volcanic Dust and Other Factors in the Production of Climatic Changes, and Their Possible Relation to Ice Ages," *Bulletin of the Mount Weather Observatory*, Washington, 1913.
———— *Rain Making and Other Weather Vagaries*, Baltimore, 1926.
———— "How Droughts Occur," *Bulletin of the American Meteorological Society*, January 1931.
———— *Physics of the Air*, New York, 1940.
Huntington, E. *The Climatic Factor as Illustrated in Arid America*, Washington, 1914.
———— *Earth and Sun*, New Haven, 1922.
———— *Civilization and Climate*, New Haven, 1922.
———— *Tree Growth and Climatic Interpretations*, Carnegie Institute of Washington, Pub. 352, 1925.
———— and Visher, S. S. *Climatic Changes*, New Haven, 1922.
Jacobs. W. C. "Synoptic Climatology," *Bulletin of the American Meteorological Society*, June 1946.
Johnson, W. D. "The High Plains and Their Utilization," *Annual Report of U.S. Geological Survey*, 21, iv, 1901, pp. 601-741.
Kendrew, W. G. *The Climates of the Continents*, Oxford, 1937.
Kimball, H. H. "Amount of Solar Radiation That Reaches the Surface of the Earth on the Land and on the Sea, and Methods by Which It Is Measured," *Monthly Weather Review*, 1928; also 1935.

——— "Variations in the Total and Luminous Solar Radiation with Geographical Position in the United States," *Monthly Weather Review*, 1919.
Kimble, G. and Bush, R. *The Weather*, New York, 1946.
*Kincer, J. B. "Precipitation and Humidity," *Atlas of American Agriculture*, Washington, 1922.
——— "The Drought of 1930," *Bulletin of the American Meteorological Society*, January 1931.
——— "Precipitation Trends," *Bulletin of the American Meteorological Society*, 1934.
——— "Climate and Weather Data for the United States," *Climate and Man*, 1941.
——— "Relation of Recent Glacier Recessions to Prevailing Temperatures," *Monthly Weather Review*, June 1940.
——— "Some Pressure-Precipitation Trend Relations," *Monthly Weather Review*, August 1941.
——— "Our Changing Climate," *Transactions of the American Geophysical Union*, June 1946.
Kollmorgen, Walter. "Rainmakers on the Plains," *Scientific Monthly*, 1935.
*Koppen, W. and Geiger, R. *Handbuch der Klimatologie*, Band II, Tech J., "The Climates of North America," Berlin, 1936.
Kullmer, C. J. "The Latitude Shift of the Storm Track in the 11-Year Solar Period," *Smithsonian Miscellaneous Collections*, 1933.
*Landsberg, H. *Physical Climatology*, State College (Pa.), 1941.
Lee, C. H. "Precipitation and Altitude in the Sierra," *Monthly Weather Review*, 1911.
Longstreth, T. M. *Knowing the Weather*, New York, 1943.
Lord, Russell. "Progress of Soil Conservation in the United States," *Geographical Journal*, London, 1945.
McDonald, W. F. *Atlas of Climatic Charts of the Oceans*, Washington, 1930.
McEwen, Geo. F. "Methods of Seasonal Weather Forecasting at the Scripps Institution of Oceanography," *Bulletin of the American Meteorological Society*, November 1934.
Mallory, Walter H. *China, Land of Famine*, New York, 1926.
Marcovitch, S. "The Measure of Droughtiness," *Monthly Weather Review*, 1930.
Marvin, C. F. "Concerning Normals, Secular Trends, and Climatic Changes," *Monthly Weather Review*, August 1923.
Mascart, J. "Notes Sur la Variabilité des Climates," *Études de Climatologie*, Lyon, 1925.
Matthes, F. E. "Report of Committee on Glaciers," *Transactions of American Geophysical Union*, 1939.
Mattice, W. A. "Weather and Corn Yields," *Monthly Weather Review*, 1931.
——— "Dust Storms," *Monthly Weather Review*, 1935.
Manson, Marsden. "The Physical and Geological Traces of the Cyclone Belt Across North America," *Monthly Weather Review*, Washington, 1924.
Miller, Eric R. "The Dustfall of November 12-13, 1933," *Monthly Weather Review*, 1934.
Mindling, G. W. "A Comparison of Drought Conditions in Georgia and Arkansas," *Monthly Weather Review*, 1933.

Mitchell, C. L. and Wexler, H. "How the Daily Forecast is Made," *Climate and Man*, 1941.

Moore, W. L. *Some Climatic Features of the Arid Regions*, U.S. Weather Bureau, 1896.

Murphy, R. C. "Oceanic and Climatic Phenomena Along the West Coast of South America During 1925," *Geographical Review*, New York, 1926.

*Namias, J. *An Introduction to the Study of Air Mass and Isentropic Analysis*, Milton, Mass., 1940.

Nelson, Enoch W. *The Influence of Precipitation and Grazing upon Black Grama Grass Range*, Washington, 1934.

Page, L. R. and Chapman, R. W. "The Dustfall of December 15-16, 1933," *American Journal of Science*, 1934.

Palmer, A. H. "Economic Results of Deficient Precipitation in California," *Monthly Weather Review*, 1920.

Parker, J. R. "Grasshoppers and Their Control," *Farmers' Bulletin No. 1828*, Washington, 1939.

Parkinson, G. R. "Dust Storms over the Great Plains; Their Causes and Forecasting," *Bulletin of the American Meteorological Society*, 1936.

Perley, Sidney. *Historic Storms of New England*, Salem, 1891.

Petterssen, Sverre. *Weather Analysis and Forecasting*, New York, 1941.

——— *Introduction to Meteorology*, New York, 1941.

Pettersson, Hans. "Meteorological Aspects of Oceanography," *Monthly Weather Review*, 1916.

Pickering, W. H. "The Relation of Prolonged Tropical Droughts to Sunspots," *Monthly Weather Review*, October 1920.

Pierce, Charles H. "The Dust Storms of November 12 and 13, 1933," *Bulletin of the American Meteorological Society*, 1934.

Reed, C. D. "Iowa Droughts," *Bulletin of the American Meteorological Society*, 1934.

——— "Droughts at New York City," *Monthly Weather Review*, November 1914.

Reed, T. R. "The North American High-Level Anticyclone," *Monthly Weather Review*, 1933.

Reed, W. W. "The Climates of the World," *Climate and Man*, 1941.

Reichelderfer, F. W. "The How and Why of Weather Knowledge," *Climate and Man*, Washington, 1941.

Richardson, Chester. "Australian Droughts," *Monthly Weather Review*, 1919.

Rossby, C. G. "The Scientific Basis of Modern Meteorology," *Climate and Man*, Washington, 1941.

Russell, R. J. "Dry Climates of the United States: II, Frequency of Dry and Desert Years 1901-20," *University of California Publications in Geography*, Vol. 5, 1932.

——— "Climatic Change Through the Ages," *Climate and Man*. Washington, 1941.

Savage, D. A. and Jacobson, L. A. "The Killing Effect of Heat and Drought on Buffalo Grass and Blue Grama Grass at Hays, Kansas," *Journal of American Society of Agronomy*, 1935.

Schell, I. I. "The Sun's Spottedness as a Possible Factor in Terrestrial Pressure," *Bulletin of the American Meteorological Society*, March, 1943.

Schreiber, P. "Die Schwankungen der Jährlichen Niederschlags höhen und deren Beziehungen zu den Relativzahlen für die Sonnenflecken," *Das Klima des Königreiches Sachsen*, 1903.

*Schulman, E. "A Bibliography of Tree-Ring Analysis," *Tree Ring Bulletin*, Tucson, April, 1940.

Sears, Paul B. *Deserts on the March*, Norman, Okla., 1935.

Shantz, H. L. "Drought Resistance and Soil Moisture," *Ecology*, 1927.

——— "The Natural Vegetation of the Great Plains Region," *Assoc. Amer. Geog. Ann.*, 1923.

Shaw, Napier. *Manual of Meteorology*, Cambridge (England), 1936

Showalter, A. K. "Relationship of Low Temperatures Aloft to Precipitation," *Transactions of American Geophysical Union*, 1939.

Siple, Paul A. "Intra-Clothing Climate," *Transactions of American Geophysical Union*, 1944.

Smith, E. H. "The International Ice-Patrol," *Meteorological Magazine*, London, 1925.

Snider, A. C. *Earth History*, New York, 1932.

Spitz, Armand. *A Start in Meteorology*, New York, 1943.

Starr, V. P. *Basic Principles of Weather Forecasting*, New York, 1942.

Stewart, George. *Storm* (includes a description of the termination of a drought by a storm from the Pacific), New York, 1941.

Stockman, W. B. "Periodic Variation of Rainfall in the Arid Region," *U.S. Weather Bureau Bulletin N*, 1904, p. 6.

Stone, R. G. "Dust Storm April 10 and 11, 1934, at Sioux City, Iowa," *Bulletin of the American Meteorological Society*, 1934.

Sverdrup, H. U. *Oceanography for Meteorologists*, New York, 1942.

Talman, C. F. "The Santa Ana," *Bulletin of the American Meteorological Society*, 1934.

The Future of the Great Plains. Document No. 144, 75th Congress, 1st Session, Washington, 1937.

The Western Range. Document No. 199, 74th Congress, 2nd Session, Washington, 1936.

Thornthwaite, C. W. "The Climates of North America According to a New Classification," *Geographical Review*, 1931.

——— **Atlas of Climatic Types in the United States*, 1900-1939, Washington, 1941.

——— and Holzman, B. *Measurement of Evaporation from Land and Water Surfaces*, Washington, 1942.

Trewartha, G. T. *An Introduction to Weather and Climate*, New York, 1943.

Union of South Africa. *Final Report of the Drought Investigation Commission*, Cape Town, 1923.

United States Department of Agriculture. *Soils and Men*, Washington, 1938.

——— *Climate and Man*, Washington, 1941.

United States Weather Bureau. "Reports on Critical Studies of Methods of Long-range Weather Forecasting," *Monthly Weather Review*, Supplement No. 39, 1939.

——— *Summaries of Climatological Data of the United States by Sections, Summaries in Bulletin W.*

Visher, S. S. "Novel American Climatic Maps and Their Interpretation," *Monthly Weather Review,* June 1943.

——— "Maps of Percentage Frequencies of Very Dry, Moderate, and Very Wet Months," *Monthly Weather Review,* March 1944.

Walford, C. "On the Famines of the World, Past and Present," *Journal of the Historical Society,* 1878-1879.

Walker, G. T. "The Liability of Drought in India as Compared with That in Other Countries," *Mem. India Met. Dept. 21,* 1912.

——— "Correlation in Seasonal Variation of Weather, IV. Sunspots and Rainfall," *Mem. India Met. Dept. 21,* 1915.

Ward, R. DeC. "Some Economic Aspects of the Heat and Drought of July, 1901, in the United States," *Bulletin American Geographical Society,* 1901.

Watson, F. H. "Note on the Dust Storm of November 13, 1933," *Science,* 1934.

Webb, W. P. *The Great Plains,* Boston, 1931.

Weightman, R. H. *Forecasting from Synoptic Weather Charts,* Washington, 1940.

Wenstrum, W. H. *Weather and the Ocean of Air,* Boston, 1942.

Wexler, H. "Formation of Polar Anticyclones," *Monthly Weather Review,* 1937.

——— and Namias, J. "Mean Monthly Isentropic Charts and Their Relation to Departures of Summer Rainfall," *Transactions of American Geophysical Union,* 1938.

Williford, C. C. "Drought," *Bulletin of the American Meteorological Society,* 1945.

Works Progress Administration. *People of the Drought States,* Washington, 1937.

Wright, W. B. *The Quarternary Ice Age,* London, 1914.

Zon, Raphael. "Climate and the Nation's Forests," *Climate and Man,* Washington, 1941.

INDEX